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DEVELOPMENT OF THE AERODYNAMIC/AEROSERVOELASTIC MODULES IN ASTROS

VOLUME 3: ZAERO APPLICATIONS MANUAL (F33615-96-C-3217)

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13. ABSTRACT (*Maximum 200 words*)

This report is a part of the documentations which describe the complete development of an STTR Phase II effort entitled, "Development of the Aerodynamic/Aeroservoelastic Modules in ASTROS." This report is one of four manuals that comprise the final report. The remaining reports consist of the ZAERO User's Manual (Volume I), the ZAERO Programmer's Manual (Volume II) and the ZAERO Theoretical Manual (Volume IV).

ASTROS* is the seamless integration of the ZAERO module into ASTROS. As an aerodynamic enhancement to ASTROS, ZAERO is the ZONA aerodynamic module, unified for all Mach number ranges. This manual assumes the reader is familiar with the ASTROS system (Version 10.0), its terminology and user interface.

This Applications Manual is divided into to Volumes. Volume I presents sample analysis cases in the flutter and static aeroelasticity disciplines that focus on the the different aerodynamic methods (i.e. subsonic, transonic, supersonic and hypersonic) within ZAERO. Volume II presents three complete optimization cases of more complicated configurations.

14. SUBJECT TERMS
Multidisciplinary Optimization, ZAERO Module, ASTROS*, Subsonic-Transonic-Supersonic-Hypersonic Aerodynamics, Aeroelasity, Aeroservoelasticity, Flutter

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FOREWORD

This final report is submitted in fulfillment of CDRL CLIN 0001, Data Item A001, Title: Scientific and Technical Reports of a Small Business Technology Transfer (STTR) Phase II contract No. F33615-96-C-3217 entitled, "Development of the Aerodynamic/Aeroservoelastic Modules in ASTROS," covering the performance period from 24 September 1996 to 24 September 1998. This document provides the sample cases demonstrating the main features of the ZAERO module in ASTROS*.

This work was performed by ZONA Technology, Inc. and its subcontractor, the University of Oklahoma (Research Institute). This work is the second phase of a continuing two-phase STTR contract supported by AFRL/Wright-Patterson. The first phase STTR contract No. F33615-95-C-3219 entitled, "Enhancement of the Aeroservoelastic Capability in ASTROS," was completed in May 1996 and published as WL-TR-96-3119. Started in September 1996, the present second phase STTR contract was conducted by the same team members as in Phase I. These contributors are: P.C. Chen (P.I.), D. Sarhaddi and D.D. Liu of ZONA Technology Inc. and Fred Striz of the University of Oklahoma.

At AFRL/Wright-Patterson, Capt. Gerald Andersen is the contract monitor and Dr. V.B. Venkayya is the initiator of the whole STTR effort. The technical advice and assistance received from Mr. Doug Niell of The MacNeal Schwendler Corporation, Dr. V.B. Venkayya and others from AFRL during the course of the present phase on the development of ASTROS* are gratefully acknowledged.

1.0 INTRODUCTION

There are four major documents that describe the ZONA Aerodynamics (ZAERO) Module which has been seamlessly integrated into the Automated STRuctural Optimization System (ASTROS). These are: the ZAERO User's, Programmer's, Application and Theoretical Manuals for ASTROS*. While ZAERO represents the ZONA Aerodynamics Module, ASTROS* is defined as the seamless integration of ZAERO into ASTROS, i.e. ASTROS* = ZAERO + ASTROS. This Applications Manual provides guidelines and sample cases to demonstrate the key features and use of the ZAERO module within ASTROS.

This Applications Manual is divided into to Volumes. Volume I presents sample analysis cases in the flutter and static aeroelasticity disciplines. Volume II provides sample optimization cases of more complex configurations.

The aerodynamic models in Volume I are kept small and are intended to demonstrate proper implementation and usage of the four ZAERO methods (i.e. ZONA6/subsonic, ZTAIC/transonic, ZONA7/supersonic and ZONA7U/hypersonic), as well as, proper aerodynamic geometry modeling and splining of the aerodynamic model to the structure.

The aerodynamic models in Volume II involve more realistic aircraft configurations and are consequently more complicated. Emphasis is placed on ASTROS* optimization using the ZAERO method.

Sections 2.0 and 3.0 comprise Volume I and present the Flutter and Static Aeroelastic cases, respectively. Many cases are taken from the MSC/NASTRAN Aeroelastic Analysis User's Guide, Version 68, and have been modified for ASTROS* input for validation of the ZAERO results.

Section 4.0 comprises Volume II of this manual and presents the static aeroelastic, normal modes and combined multidisciplinary (MDO) optimization cases.

VOLUME I

Flutter and Static Aeroelastic Analysis Cases

2.0 FLUTTER CASES

2.1 Case 1: Subsonic (M=0.45) Flutter Analysis of a 15-Degree Sweptback Wing (HA145E)

- ***Purpose:*** Demonstrate a wing only, subsonic (i.e. ZONA6 method) flutter case using the P-K and K flutter solution methods.

- ***Description of Input:***

A 15 degree sweptback wing (modified HA145E case from the MSC/NASTRAN Aeroelastic Analysis User's Guide, Version 68) is considered for this case. The structural and aerodynamic models are shown in Fig 2.1.1.

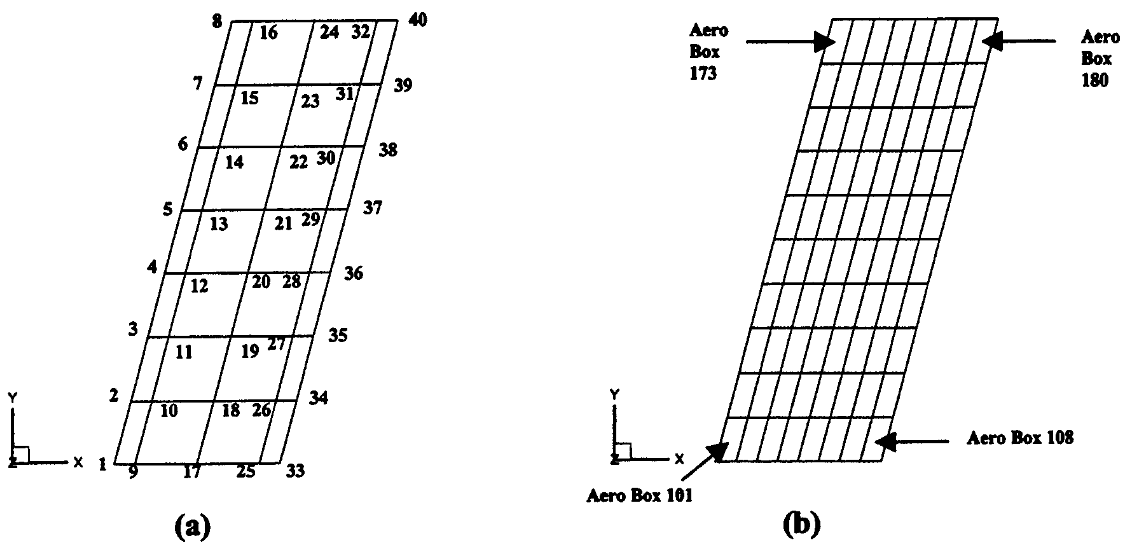


Figure 2.1.1 15 Degree Sweptback Wing (a) Structural Model and (b) Aerodynamic Model.

- *Solution Control*

An analysis run is performed with the MODES and FLUTTER disciplines. The BOUNDARY condition specifies SPC = 1 that selects the single-point constraints for grid points, REDUCE = 25 that selects the analysis set degrees of freedom, and METHOD = 10 that selects the eigenvalue extraction method to be used.

- *Structural Model*

The reader is referred to the MSC/NASTRAN Aeroelastic Analysis User's Guide, Version 68 for a description of the structural model.

- Aerodynamic Parameters / Flight Conditions

The **AEROZ** bulk data card specifies a symmetric model about the x-z plane. A reference density of 1.1092E-07 slinches (sea level density) and reference length of 2.07055 inches are used.

The **MKAEROZ** bulk data card specifies a freestream Mach number of 0.45 and 10 reduced frequencies from 0.0001 to 0.20.

- Aerodynamic Model

One **CAERO7** wing macroelement is defined with 8 chordwise and 10 spanwise evenly cut aerodynamic boxes. Root and tip chord lengths are both 2.07055 inches with a 5.5251 inch semispan length. The wing tip x- and y- coordinates are located at 1.48044 and 5.5251 inches, respectively, establishing a 15 degree leading edge sweep angle.

- Spline

A **SPLINE1** bulk data card is used to spline the aerodynamic wing model to the structure. A **PANLST2** bulk data card is referenced by SETK = 101 and a **SET1** bulk data card by SETG = 100. The **PANLST2** defines the wing macroelement to be splined (**CAERO7** with WID of 101), and splines all of the wing aerodynamic boxes (101 through 180) to the structural grid points listed in the **SET1** bulk data card (see Input Data Listing 2.1 for **SET1 GRID** point id's and Fig 2.1.1.a).

- Flutter

A **FLUTTER** bulk data card with SETID=30 requests that the P-K and K methods be used (METHOD entry set to PKK). The DENS entry refers to an **FLFACT** bulk data card with SID=1 that lists the density ratios for this case. The IDMK=1000 entry refers to the **MKAEROZ** bulk data card for this flutter case establishing the Mach number and reduced frequencies to be used. Finally, the VEL entry refers to an **FLFACT** bulk data card that lists the velocities to be used by the P-K flutter analysis method.

- ***Description of Output:***

Two disciplines were performed in this ASTROS* run – a modal analysis and flutter analysis. The structural natural frequencies and generalized mass for the first four modes generated by the ASTROS* modal analysis is shown in Table 2.1.1 along with the MSC/NASTRAN results.

Table 2.1.1 Natural Frequencies and Generalized Mass of Case HA145E.

Mode No.	ASTROS*		MSC/NASTRAN	
	Natural Frequency (Hz)	Generalized Mass	Natural Frequency (Hz)	Generalized Mass
1	34.7220	2.4861E-05	34.3439	2.4855E-05
2	211.469	8.7983E-06	210.000	9.0881E-06
3	260.147	8.6338E-06	260.429	8.5232E-06
4	645.657	7.4457E-06	634.761	7.9439E-06

The flutter results using ZONA6 aerodynamics of ASTROS* by both the P-K and K methods are compared with that of MSC/NASTRAN using DLM with the KE method (see Fig 2.1.2).

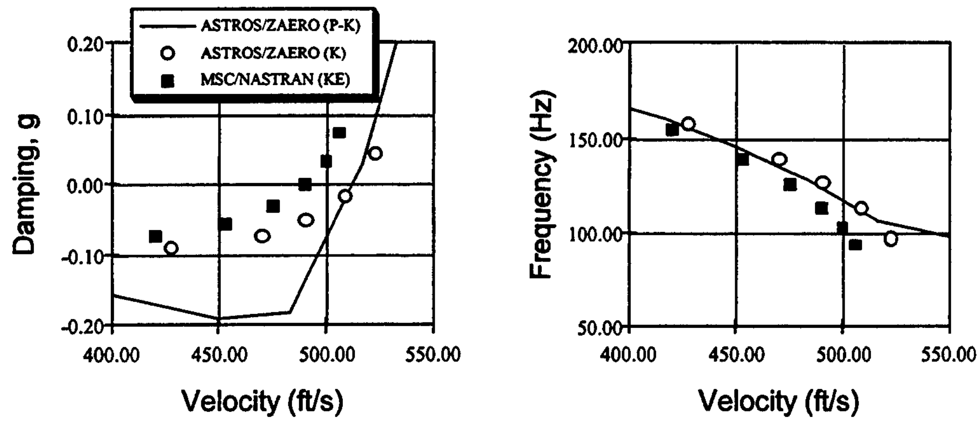


Figure 2.1.2 Flutter Results of Case HA145E, M=0.45.

Excellent agreement in terms of flutter speed at zero damping between the ASTROS* P-K and K methods is obtained validating the K method. However, a small difference of flutter speed is observed between ASTROS* and MSC/NASTRAN. This difference is most likely caused by the differences in the data obtained from the dynamic analyses (Table 2.1.1).

- ***Input Data Listing:***

Listing 2.1 Input Data for the 15 Degree Sweptback Wing (HA145E).

```
ASSIGN DATABASE ICWCU3 PASS NEW DELETE
SOLUTION
TITLE = ZAERO FLUTTER CASE (HA145E): HALF SPAN 15-DEG SWEPT UNTAPERED WING
SUBTIT = PK & K-METHOD OF FLUTTER ANALYSIS
ANALYZE
   PRINT ROOTS = ALL
   BOUNDARY SPC = 1, REDUCE = 25, METHOD = 10
      LABEL = MODAL ANALYSIS
      MODES
      FLUTTER (FLCOND=30)
      LABEL = SUBSONIC CASE M=0.45
END
BEGIN BULK
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
GRID    1               0.0     0.0     0.0
GRID    2               .211491 .7893   0.0
GRID    3               .422983 1.5786  0.0
GRID    4               .634474 2.3679  0.0
GRID    5               .845966 3.1572  0.0
GRID    6               1.05746 3.9465  0.0
GRID    7               1.26895 4.7358  0.0
GRID    8               1.48044 5.5251  0.0
GRID    9               .258819 0.0     0.0
GRID    10              .47031  .7893   0.0
GRID    11              .681802 1.5786  0.0
GRID    12              .893293 2.3679  0.0
GRID    13              1.10478 3.1572  0.0
GRID    14              1.31628 3.9465  0.0
GRID    15              1.52777 4.7358  0.0
GRID    16              1.73926 5.5251  0.0
GRID    17              1.03528 0.0     0.0
GRID    18              1.24677 .7893   0.0
GRID    19              1.45826 1.5786  0.0
GRID    20              1.66975 2.3679  0.0
GRID    21              1.88124 3.1572  0.0
GRID    22              2.09273 3.9465  0.0
GRID    23              2.30422 4.7358  0.0
GRID    24              2.51572 5.5251  0.0
GRID    25              1.81173 0.0     0.0
GRID    26              2.02322 .7893   0.0
GRID    27              2.23471 1.5786  0.0
GRID    28              2.44621 2.3679  0.0
```

```
GRID    29              2.6577  3.1572  0.0
GRID    30              2.86919 3.9465  0.0
GRID    31              3.08068 4.7358  0.0
GRID    32              3.29217 5.5251  0.0
GRID    33              2.07055 0.0     0.0
GRID    34              2.28204 .7893   0.0
GRID    35              2.49353 1.5786  0.0
GRID    36              2.70502 2.3679  0.0
GRID    37              2.91652 3.1572  0.0
GRID    38              3.12801 3.9465  0.0
GRID    39              3.3395  4.7358  0.0
GRID    40              3.55099 5.5251  0.0
$                                                                       $
CQUAD4  1       1       1       2       10      9                       +M00000
+M00000                 .001    .001     .041    .041
CQUAD4  2       1       2       3       11      10                      +M00001
+M00001                 .001    .001     .041    .041
CQUAD4  3       1       3       4       12      11                      +M00002
+M00002                 .001    .001     .041    .041
CQUAD4  4       1       4       5       13      12                      +M00003
+M00003                 .001    .001     .041    .041
CQUAD4  5       1       5       6       14      13                      +M00004
+M00004                 .001    .001     .041    .041
CQUAD4  6       1       6       7       15      14                      +M00005
+M00005                 .001    .001     .041    .041
CQUAD4  7       1       7       8       16      15                      +M00006
+M00006                 .001    .001     .041    .041
CQUAD4  8       1       9       10      18      17
CQUAD4  9       1       10      11      19      18
CQUAD4  10      1       11      12      20      19
CQUAD4  11      1       12      13      21      20
CQUAD4  12      1       13      14      22      21
CQUAD4  13      1       14      15      23      22
CQUAD4  14      1       15      16      24      23
CQUAD4  15      1       17      18      26      25
CQUAD4  16      1       18      19      27      26
CQUAD4  17      1       19      20      28      27
CQUAD4  18      1       20      21      29      28
CQUAD4  19      1       21      22      30      29
CQUAD4  20      1       22      23      31      30
CQUAD4  21      1       23      24      32      31
CQUAD4  22      1       25      26      34      33                      +M00007
+M00007                  .041    .041   .001    .001
CQUAD4  23      1       26      27      35      34                      +M00008
+M00008                  .041    .041   .001    .001
CQUAD4  24      1       27      28      36      35                      +M00009
+M00009                  .041    .041   .001    .001
CQUAD4  25      1       28      29      37      36                      +M00010
+M00010                  .041    .041   .001    .001
CQUAD4  26      1       29      30      38      37                      +M00011
+M00011                  .041    .041   .001    .001
CQUAD4  27      1       30      31      39      38                      +M00012
+M00012                  .041    .041   .001    .001
CQUAD4  28      1       31      32      40      39                      +M00013
+M00013                  .041    .041   .001    .001
$                                                                       $
PSHELL  1       1       .041    1               1
$                                                                       $
CONVERT MASS    .0025901
$                                                                       $
MFORM    COUPLED
$                                                                       $
MAT1    1       9.2418+63.4993+6        0.097464
$                                                                       $
SPC1    1       12345   9
SPC1    1       12345   25
SPC1    1       6       1       THRU    40
$                                                                       $
ASET1   25      3        1      THRU     8
ASET1   25      3       10      THRU    24
ASET1   25      3       26      THRU    40
$                                                                       $
EIGR    10      MGIV                             4                      +ER
+ER     MAX
$                                                                       $
$ * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * $
$                                                                       $
$                       Z A E R O    I N P U T                          $
$                                                                       $
$ * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * $
$                                                                       $
$ THIS CASE DEMONSTRATES A SINGLE WING, SUBSONIC FLUTTER CASE USING     $
$ THE PK AND K FLUTTER SOLUTION METHODS.                                $
$                                                                       $
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
$                                                                       $
$                                                                       $
$               * AERO PARAMETERS / FLIGHT CONDITIONS *                 $
$                                                                       $
$                                                                       $
$       ACSID   XZSYM   RHOREF  REFC    REFB    REFS    GREF            $
AEROZ   0       YES     1.1092-72.07055 1.      1.
$                                                                       $
$       IDMK    MACH    METHOD  IDFLT   SAVE    <--FILENAME-->  PRINT   $
MKAEROZ 1000    .45                                             0       +MK1
$       FREQ1   FREQ2   ETC                                             $
+MK1    0.001   0.05    0.10    0.11    0.12    0.13    0.14    0.16    +MK2
```

```
+MK2    0.18    0.20
$                                                                       $
$                                                                       $
$                       * WING MACROELEMENT *                           $
$                                                                       $
$                                                                       $
$       WID     LABEL   ACOORD  NSPAN   NCHORD  LSPAN   ZTAIC   PAFOIL7 $
CAERO7  101     WING    0       11      9                               +CA101
$       XRL     YRL     ZRL     RCH     LRCHD   ATTCHR                  $
+CA101  .0      .0      .0      2.07055 0       0                       +CA102
$       XRT     YRT     ZRT     TCH     LTCHD   ATTCHT                  $
+CA102  1.48044 5.52510 0.0     2.07055 0       0
$                                                                       $
$                                                                       $
$                   * SURFACE SPLINE FIT ON THE WING *                  $
$                                                                       $
$                                                                       $
$       EID     MODEL   CP      SETK    SETG    DZ      EPS
SPLINE1 100     WING            101     100     0.0
$                                                                       $
$       SETID   MACROID BOX1    BOX2    ETC                             $
PANLST2 101     101     101     THRU    180
$                                                                       $
$       SID     G1      G2      ETC
SET1    100     2       4       6       8       9       11      13      +S1
+S1     15      18      20      22      24      25      27      29      +S2
+S2     31      34      36      38      40
$                                                                       $
$                                                                       $
$                       * FLUTTER ANALYSIS *                            $
$                                                                       $
$                                                                       $
$        SETID  METHOD  DENS    IDMK    VEL     MLIST   KLISTE  EFFID   $
FLUTTER 30      PKK     1       1000    3                               +FL1
$        SYMXZ  SYMXY   EPS     CURVFIT PRINT                           $
+FL1    +1
$                                                                       $
$       SID     F1      F2      ETC                                     $
FLFACT  1       0.967
FLFACT  3       4000.   5000.   6000.   7000.   8000.   9000.   10000.
$                                                                       $
$                                                                       $
ENDDATA
```

2.2 Case 2: Low Supersonic (M=1.3) Flutter Analysis of a 15-Degree Sweptback Wing (HA145FB) With and Without Thickness Effect

- ***Purpose:*** Demonstrate a wing only low supersonic flutter case with and without thickness effects using the P-K and K methods.

- ***Description of Input:***

The same 15 degree sweptback wing presented in Case 1 is considered here. It is a modified sample test case from the MSC/NASTRAN Aeroelastic Analysis User's Guide, Version 68 (case HA145FB). Both the structural and aerodynamic models for this case were shown in Fig 2.1.1.

This case presents both the flat plate results (ZONA7 aerodynamics) and the wing with supersonic thickness effect results (ZONA7U aerodynamics) of a hexagonal wing cross section (Tuovila, W.J., NACA RM L55E11, 1955). The wing planform and cross section are shown in Fig 2.2.1.

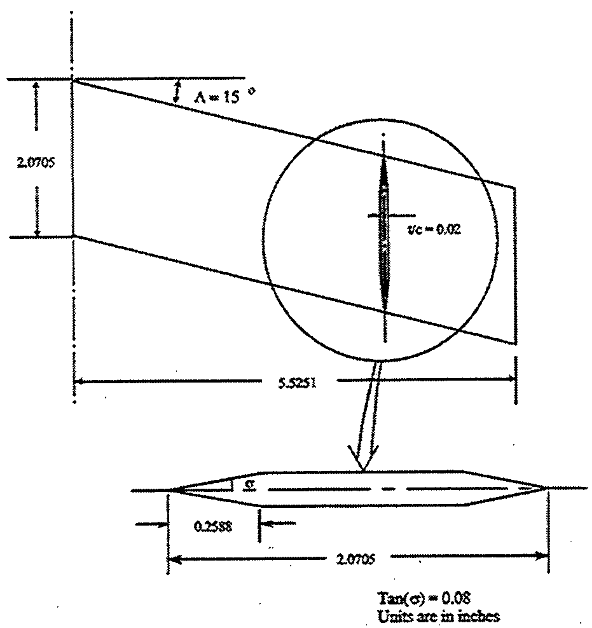


Figure 2.2.1 15 Degree Sweptback Planform and Cross Section (Tuovila, W.J., NACA RM L55E11, 1955).

- Solution Control

An analysis run is performed with the MODES and FLUTTER disciplines. The BOUNDARY condition specifies SPC = 1 that selects the single-point constraints for grid points, REDUCE = 25 that selects the analysis set degrees of freedom, and METHOD = 10 that selects the eigenvalue extraction method to be used. Two flutter cases are requested. The first FLCOND = 30 selects the flutter case with no thickness effect and the second FLCOND = 40 selects the flutter case with the supersonic thickness effect.

- Structural Model

The reader is referred to the MSC/NASTRAN Aeroelastic Analysis User's Guide, Version 68 for a description of the structural model.

- Aerodynamic Parameters / Flight Conditions

The **AEROZ** bulk data card specifies a symmetric model about the x-z plane. A reference density of 1.145E-07 slinches (sea level density) and reference length of 2.07055 inches are used.

Two **MKAEROZ** bulk data cards are used to specify a freestream Mach number of 1.3 and 8 reduced frequencies ranging from 0.0001 to 0.08. Although both **MKAEROZ** bulk data cards have the same Mach number and reduced frequency input, two cards are required to compute both Aerodynamic Influence Coefficient (AIC) matricies using the linear aerodynamics method (ZONA7) and the nonlinear aerodynamics method (ZONA7U) which includes the supersonic thickness effect.

- Aerodynamic Model

One **CAERO7** wing macroelement is defined with 8 chordwise and 10 spanwise evenly cut aerodynamic boxes. Root and tip chord lengths are both 2.07055 inches with a 5.5251 inch semispan length. The wing tip x- and y- coordinates are located at 1.48044 and 5.5251 inches, respectively, establishing a 15 degree leading edge sweep angle.

A **PAFOIL7** bulk data card is used to define the 2% thick hexagonal airfoil section. The ITAX entry refers to an **AEFACT** bulk data card that specifies four x-coordinate points in percentage of the airfoil chord length. ITAX is a negative integer to request that linear interpolation be used between the airfoil points. The ITHR/T and ICAMR/T entries refer to **AEFACT** bulk data cards that specify the airfoil wing root and tip half thickness and cambers, respectively, at each x-coordinate.

- Spline

A **SPLINE1** bulk data card is used to spline the aerodynamic wing model to the structure. A **PANLST2** bulk data card is referenced by the SETK = 101 entry and a **SET1** bulk data card by the SETG = 100 entry. The **PANLST2** defines the wing macroelement to be splined (**CAERO7** with WID of 101), and splines all of the wing aerodynamic boxes (101 through 180) to the structural grid points listed in the **SET1** bulk data card (see Input Data Listing 2.2 for **SET1 GRID** point id's and Fig 2.1.1).

- Flutter

Two **FLUTTER** bulk data cards are used to perform two separate flutter analyses; one <u>without</u> thickness effects (IDMK=1000 entry refers to the **MKAEROZ** bulk data card employing the linear ZONA7 method at Mach 1.3) and one <u>with</u> the wing thickness effects (IDMK=2000 entry refers to the **MKAEROZ** bulk data card employing the nonlinear ZONA7U method at Mach 1.3). Both **FLUTTER** cards request that the P-K and K methods be used (METHOD entry set to PKK) and use the same density ratio and velocities specified in the **FLFACT** bulk data cards with SID=1 and 3, respectively.

- ***Description of Output:***

The flutter results using ZONA7 aerodynamics of ASTROS* are compared with results from the ZONA51 method of MSC/NASTRAN (i.e. Aero Option II). Excellent agreement between the two methods are obtained (see Table 2.2.1). This is expected since the lifting surface part of ZONA7 is identical to that of ZONA51.

Table 2.2.1 Flutter Results of Case HA145FB ($M = 1.3$, $\sigma = 0.20606$).

	V_f (ft/s)	f_f (Hz)
Test	1280	102
W.P. Rodden	1405	129
	MSC/NASTRAN P-K Method	
MSC/NASTRAN (ZONA51)	1576	132
	ASTROS* K Method / P-K Method	
ZONA7 (no thickness)	1583 / 1601	132 / 130
ZONA7U (thickness effect)	1415 / 1426	123 / 122

σ = Density Ratio = ρ / ρ_{sl}

- ***Input Data Listing:***

Listing 2.2 Input Data for the 15 Degree Sweptback Wing With and Without Thickness (HA145FB).

```
ASSIGN DATABASE ICWCU3 PASS NEW DELETE
SOLUTION
TITLE = ZAERO FLUTTER CASE (HA145FB): HALF SPAN 15-DEG SWEPT UNTAPERED WING
SUBTIT  = PK & K-METHOD OF FLUTTER ANALYSIS, ZONA7 + ZONA7U
ANALYZE
   PRINT  ROOTS=ALL
   BOUNDARY SPC = 1, REDUCE = 25, METHOD = 10
      LABEL = MODAL ANALYSIS
      MODES
      FLUTTER (FLCOND=30)
      LABEL = WITHOUT THICKNESS
      FLUTTER (FLCOND=40)
      LABEL = WITH THICKNESS
END
BEGIN BULK
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
GRID    1               0.0     0.0     0.0
GRID    2               .211491 .7893   0.0
GRID    3               .422983 1.5786  0.0
GRID    4               .634474 2.3679  0.0
GRID    5               .845966 3.1572  0.0
GRID    6               1.05746 3.9465  0.0
GRID    7               1.26895 4.7358  0.0
GRID    8               1.48044 5.5251  0.0
GRID    9               .258819 0.0     0.0
GRID    10              .47031  .7893   0.0
GRID    11              .681802 1.5786  0.0
GRID    12              .893293 2.3679  0.0
GRID    13              1.10478 3.1572  0.0
GRID    14              1.31628 3.9465  0.0
GRID    15              1.52777 4.7358  0.0
GRID    16              1.73926 5.5251  0.0
GRID    17              1.03528 0.0     0.0
GRID    18              1.24677 .7893   0.0
GRID    19              1.45826 1.5786  0.0
GRID    20              1.66975 2.3679  0.0
GRID    21              1.88124 3.1572  0.0
GRID    22              2.09273 3.9465  0.0
GRID    23              2.30422 4.7358  0.0
GRID    24              2.51572 5.5251  0.0
GRID    25              1.81173 0.0     0.0
GRID    26              2.02322 .7893   0.0
```

```
GRID    27              2.23471 1.5786  0.0
GRID    28              2.44621 2.3679  0.0
GRID    29              2.6577  3.1572  0.0
GRID    30              2.86919 3.9465  0.0
GRID    31              3.08068 4.7358  0.0
GRID    32              3.29217 5.5251  0.0
GRID    33              2.07055 0.0     0.0
GRID    34              2.28204 .7893   0.0
GRID    35              2.49353 1.5786  0.0
GRID    36              2.70502 2.3679  0.0
GRID    37              2.91652 3.1572  0.0
GRID    38              3.12801 3.9465  0.0
GRID    39              3.3395  4.7358  0.0
GRID    40              3.55099 5.5251  0.0
$                                                                       $
CQUAD4  1       1       1       2       10      9                       +M00000
+M00000                 .001    .001    .041    .041
CQUAD4  2       1       2       3       11      10                      +M00001
+M00001                 .001    .001    .041    .041
CQUAD4  3       1       3       4       12      11                      +M00002
+M00002                 .001    .001    .041    .041
CQUAD4  4       1       4       5       13      12                      +M00003
+M00003                 .001    .001    .041    .041
CQUAD4  5       1       5       6       14      13                      +M00004
+M00004                 .001    .001    .041    .041
CQUAD4  6       1       6       7       15      14                      +M00005
+M00005                 .001    .001    .041    .041
CQUAD4  7       1       7       8       16      15                      +M00006
+M00006                 .001    .001    .041    .041
CQUAD4  8       1       9       10      18      17
CQUAD4  9       1       10      11      19      18
CQUAD4  10      1       11      12      20      19
CQUAD4  11      1       12      13      21      20
CQUAD4  12      1       13      14      22      21
CQUAD4  13      1       14      15      23      22
CQUAD4  14      1       15      16      24      23
CQUAD4  15      1       17      18      26      25
CQUAD4  16      1       18      19      27      26
CQUAD4  17      1       19      20      28      27
CQUAD4  18      1       20      21      29      28
CQUAD4  19      1       21      22      30      29
CQUAD4  20      1       22      23      31      30
CQUAD4  21      1       23      24      32      31
CQUAD4  22      1       25      26      34      33                      +M00007
+M00007                 .041    .041    .001    .001
CQUAD4  23      1       26      27      35      34                      +M00008
+M00008                 .041    .041    .001    .001
CQUAD4  24      1       27      28      36      35                      +M00009
+M00009                 .041    .041    .001    .001
CQUAD4  25      1       28      29      37      36                      +M00010
+M00010                 .041    .041    .001    .001
CQUAD4  26      1       29      30      38      37                      +M00011
+M00011                 .041    .041    .001    .001
CQUAD4  27      1       30      31      39      38                      +M00012
+M00012                 .041    .041    .001    .001
CQUAD4  28      1       31      32      40      39                      +M00013
+M00013                 .041    .041    .001    .001
$                                                                       $
PSHELL  1       1       .041    1               1
$                                                                       $
CONVERT MASS    .0025901
$                                                                       $
MFORM   COUPLED
$                                                                       $
MAT1    1       9.2418+63.4993+6        0.097464
$                                                                       $
SPC1    1       12345   9
SPC1    1       12345   25
SPC1    1       6       1       THRU    40
$                                                                       $
ASET1   25      3       1       THRU    8
ASET1   25      3       10      THRU    24
ASET1   25      3       26      THRU    40
$                                                                       $
EIGR    10      MGIV                            6                       +ER
+ER     MAX
$                                                                       $
$ * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * $
$                                                                       $
$                       Z A E R O   I N P U T                           $
$                                                                       $
$ * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * $
$                                                                       $
$ THIS CASE DEMONSTRATES A SINGLE WING, LOW SUPERSONIC FLUTTER CASE      $
$ WITH AND WITHOUT WING THICKNESS EFFECTS (I.E. ZONA7 AND ZONA7U        $
$ METHODS, RESPECTIVELY) USING THE PK AND K FLUTTER SOLUTION METHODS.   $
$                                                                       $
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
$                                                                       $
$                                                                       $
$               * AERO PARAMETERS / FLIGHT CONDITIONS *                 $
$                                                                       $
$                                                                       $
$       ACSID   XZSYM   RHOREF  REFC    REFB    REFS    GREF            $
AEROZ   0       YES     1.145-7 2.07055 1.      1.
$                                                                       $
$                                                                       $
```

```
$ TWO MKAEROZ BULK DATA CARDS ARE USED. THE FIRST MKAEROZ ACTIVATES THE $
$ LINEAR METHOD (ZONA7) AND THE SECOND THE NONLINEAR METHOD (ZONA7U)    $
$ VIA THE METHOD FLAG.  EACH MKAEROZ CARD IS REFERENCED BY A FLUTTER    $
$ CARD BELOW.                                                           $
$                                                                       $
$       IDMK    MACH    METHOD  IDFLT   SAVE    <--FILENAME--> PRINT    $
MKAEROZ 1000    1.3     0                                               +MK1
$       FREQ1   FREQ2   ETC                                             $
+MK1    0.0001  0.02    0.03    0.04    0.05    0.06    0.07    0.08
$                                                                       $
MKAEROZ 2000    1.3     1                                               +MK2
+MK2    0.0001  0.02    0.03    0.04    0.05    0.06    0.07    0.08
$                                                                       $
$                                                                       $
$                      * WING MACROELEMENT *                            $
$                                                                       $
$                                                                       $
$       WID     LABEL   ACOORD  NSPAN   NCHORD  LSPAN   ZTAIC   PAFOIL7 $
CAERO7  101     WING    0       11      9                       100     +CA101
$       XRL     YRL     ZRL     RCH     LRCHD   ATTCHR                  $
+CA101  0.0     0.0     0.0     2.07055 0       0                       +CA102
$       XRT     YRT     ZRT     TCH     LTCHD   ATTCHT                  $
+CA102  1.48044 5.52510 0.0     2.07055 0       0
$                                                                       $
$ THE PAFOIL7 CARD IS USED TO DEFINE THE AIRFOIL THICKNESS ALLOWING     $
$ FOR THE INPUT OF HALF THICKNESS, CAMBER AND LEADING EDGE RADII AT     $
$ THE WING ROOT AND TIP.  THICKNESS AND CAMBER DISTRIBUTIONS BETWEEN    $
$ THE WING ROOT AND TIP ARE INTERPOLATED. FOR THIS CASE, A 2% THICK     $
$ HEXAGONAL AIRFOIL SECTION IS DEFINED. A NEGATIVE VALUE OF ITAX        $
$ REQUESTS THAT A LINEAR INTERPOLATION BE USED FOR THICKNESS AND        $
$ CAMBER DISTRIBUTIONS (POSITIVE VALUE IS FOR CUBIC INTERPOLATION).     $
$ THICKNESS AND CAMBER DISTRIBUTIONS ARE USED ONLY FOR SUPERSONIC       $
$ THICKNESS EFFECTS (ZONA7U) WHEN THE 'METHOD' ENTRY IS ACTIVE IN       $
$ MKAEROZ BULK DATA CARD.                                               $
$                                                                       $
$       ID      ITAX    ITHR    ICAMR   RADR    ITHT    ICAMT   RADT    $
PAFOIL7 100     -101    102     103     0.0     102     103     0.0
$                                                                       $
$       SID     D1      D2      ETC
AEFACT  101     0.0     12.5    87.5    100.
AEFACT  102     0.0     1.0     1.0     0.0
AEFACT  103     0.0     0.0     0.0     0.0
$                                                                       $
$                                                                       $
$                 * SURFACE SPLINE FIT ON THE WING *                    $
$                                                                       $
$                                                                       $
$       EID     MODEL   CP      SETK    SETG    DZ      EPS             $
SPLINE1 100     WING            101     100     0.0
$                                                                       $
$       SETID   MACROID BOX1    BOX2    ETC                             $
PANLST2 101     101     101     THRU    180
$                                                                       $
$       SID     G1      G2      ETC                                     $
SET1    100     2       4       6       8       9       11      13      +S1
+S1     15      18      20      22      24      25      27      29      +S2
+S2     31      34      36      38      40
$                                                                       $
$                                                                       $
$                                                                       $
$                      * * FLUTTER ANALYSIS * *                         $
$                                                                       $
$                                                                       $
$ THE FLUTTER BULK DATA CARDS EMPLOY THE PK AND K FLUTTER SOLUTION      $
$ METHODS.  EACH FLUTTER CARD REFERS TO A DIFFERENT MKAEROZ BULK DATA   $
$ CARD.  THE FIRST FLUTTER CASE REFERS TO AN MKAEROZ CARD WITH AN IDMK  $
$ OF 1000 (WING WITHOUT THICKNESS CASE - ZONA7 AERODYNAMICS).  THE      $
$ SECOND FLUTTER CASE REFERS TO AN MKAEROZ CARD WITH IDMK = 2000        $
$ (WING WITH THICKNESS CASE - ZONA7U AERODYNAMICS).                     $
$                                                                       $
$        SETID  METHOD  DENS    IDMK    VEL     MLIST   KLIST   EFFID   $
FLUTTER 30      PKK     1       1000    3                               +FL1
$        SYMXZ  SYMXY   EPS     CURVFIT PRINT                           $
+FL1    1
$                                                                       $
FLUTTER 40      PKK     1       2000    3                               +FL2
+FL2    1
$                                                                       $
$       SID     F1      F2      ETC                                     $
FLFACT  1       .20606
FLFACT  3       14400.  15600.  16800.  18000.  19200.  20400.
ENDDATA
```

2.3 Case 3: High Supersonic (M=3.0) Flutter Analysis of a 15-Degree Sweptback Wing (HA145G) With and Without Thickness Effect

- ***Purpose:*** Demonstrate a wing only, with and without thickness effect, high supersonic flutter case using the P-K and K methods.

- ***Description of Input:***

The same 15 degree sweptback wing presented in Case 1 is considered. It is a modified sample test case from the MSC/NASTRAN Aeroelastic Analysis User's Guide (case HA145G). Both the structural and aerodynamic models were shown in Fig 2.1.1.

This case presents both the flat plate result (ZONA7 aerodynamics) and the wing with supersonic thickness effect result (ZONA7U aerodynamics) of a hexagonal wing cross section (Tuovila, W.J., NACA RM L55E11, 1955). The wing planform and cross section were shown in Fig 2.2.1.

There are two differences between the present case and Case 2. First, the Mach number for the present case is 3.0, whereas, Case 2 was 1.3. Second, the material properties (i.e. **MAT1** bulk data card) of the wing are different than that of Case 2. The wing of Case 2 was made of aluminum while the wing of Case 3 is made of magnesium. The nominal properties of magnesium include a moduli of elasticity $E = 6.0 \times 10^6$ and $G = 2.4 \times 10^6$ psi, with a density of 0.064 lb/in^3. These moduli and density were adjusted to match experimental data. The adjusted values, used in the present **MAT1** card, are $E = 6.3604 \times 10^6$, $G = 2.5442 \times 10^6$ psi and a density of 0.0626202 lb/in^3.

- Solution Control

An analysis run is performed with the MODES and FLUTTER disciplines. The BOUNDARY condition specifies SPC = 1 that selects the single-point constraints for grid points, REDUCE = 25 that selects the analysis set degrees of freedom, and METHOD = 10 that selects the eigenvalue extraction method to be used. Two flutter cases are requested. The first FLCOND = 30 selects the flutter case with no thickness effect and the second FLCOND = 40 selects the flutter case with the supersonic thickness effect.

- Structural Model

The reader is referred to the MSC/NASTRAN Aeroelastic Analysis Guide for a description of the structural model.

- Aerodynamic Parameters / Flight Conditions

The **AEROZ** bulk data card specifies a symmetric model about the x-z plane. A reference density of 1.145E-07 slinches (sea level density) and reference length of 2.07055 inches are used.

Two **MKAEROZ** bulk data cards are used to specify a freestream Mach number of 3.0 and 8 reduced frequencies ranging from 0.0001 to 0.08. Although both **MKAEROZ** bulk data cards have the same Mach number and reduced frequency input, two cards are required to compute both Aerodynamic Influence Coefficient (AIC) matricies using the linear aerodynamics method (ZONA7) and the nonlinear aerodynamics method (ZONA7U) which includes the supersonic thickness effect.

- Aerodynamic Model

One **CAERO7** wing macroelement is defined with 8 chordwise and 10 spanwise evenly cut aerodynamic boxes. Root and tip chord lengths are both 2.07055 inches with a 5.5251 inch semispan length. The wing tip x and y coordinates are located at 1.48044 and 5.5251 inches, respectively, establishing a 15 degree leading edge sweep angle.

A **PAFOIL7** bulk data card is used to define the 2% thick hexagonal airfoil section. The ITAX entry refers to an **AEFACT** bulk data card that specifies four x-coordinate points in percentage of the airfoil chord length. ITAX is a negative integer to request that linear interpolation be used between the airfoil points. The ITHR/T and ICAMR/T entries refer to **AEFACT** bulk data cards that specify the airfoil wing root and tip half thickness and cambers, respectively, at each x-coordinate.

- Spline

A **SPLINE1** bulk data card is used to spline the aerodynamic wing model to the structure. A **PANLST2** bulk data card is referenced by the SETK = 101 entry and a **SET1** bulk data card by the SETG = 100 entry. The **PANLST2** defines the wing macroelement to be splined (**CAERO7** with WID of 101), and splines all of the wing aerodynamic boxes (101 through 180) to the structural grid points listed in the **SET1** bulk data card (see Input Data Listing 2.3 for **SET1 GRID** point id's and Fig 2.1.1).

- Flutter

Two **FLUTTER** bulk data cards are used to perform two separate flutter analyses; one <u>without</u> thickness effects (IDMK=1000 entry refers to the **MKAEROZ** bulk data card employing the linear ZONA7 method at Mach 3.0) and one <u>with</u> the wing thickness effects (IDMK=2000 entry refers to the **MKAEROZ** bulk data card employing the nonlinear ZONA7U method at Mach 3.0). Both **FLUTTER** cards request that the P-K and K methods be used (METHOD entry set to PKK) and use the same density ratio and velocities specified in the **FLFACT** bulk data cards with SID=1 and 3, respectively.

• ***Description of Output:***

The flutter results using ZONA7 aerodynamics of ASTROS* are compared with results from the ZONA51 method of MSC/NASTRAN (i.e. Aero Option II). Excellent agreement between the two methods are obtained (see Table 2.3.1). This is expected since the lifting surface part of ZONA7 is identical to that of ZONA51.

Table 2.3.1 Flutter Results of Case HA145FB (M = 3.0, σ = 0.391).

	V_f (ft/s)	f_f (Hz)
Test	2030	146
W.P. Rodden	2077	149
ASTROS* K Method / P-K Method		
ZONA7 (no thickness)	2369 / 2448	158 / 154
ZONA7U (thickness effect)	1897 / 1923	154 / 152

σ = Density Ratio = ρ / ρ_{sl}

• *Input Data Listing:*

Listing 2.3 Input Data for the 15 Degree Sweptback Wing With and Without Thickness (HA145G).

```
ASSIGN DATABASE ICWCU3 PASS NEW DELETE
SOLUTION
TITLE = ZAERO FLUTTER CASE (HA145G): HALF SPAN 15-DEG SWEPT UNTAPERED WING
SUBTIT = PK & K METHOD OF FLUTTER ANALYSIS, ZONA7 + ZONA7U
ANALYZE
   PRINT  ROOTS=ALL
   BOUNDARY SPC = 1, REDUCE = 25, METHOD = 10
      LABEL = MODAL ANALYSIS
      MODES
      LABEL = WITHOUT THICKNESS
      FLUTTER (FLCOND=30)
      LABEL = WITH THICKNESS
      FLUTTER (FLCOND=40)
END
BEGIN BULK
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
GRID    1               0.0     0.0     0.0
GRID    2               .211491 .7893   0.0
GRID    3               .422983 1.5786  0.0
GRID    4               .634474 2.3679  0.0
GRID    5               .845966 3.1572  0.0
GRID    6               1.05746 3.9465  0.0
GRID    7               1.26895 4.7358  0.0
GRID    8               1.48044 5.5251  0.0
GRID    9               .258819 0.0     0.0
GRID    10              .47031  .7893   0.0
GRID    11              .681802 1.5786  0.0
GRID    12              .893293 2.3679  0.0
GRID    13              1.10478 3.1572  0.0
GRID    14              1.31628 3.9465  0.0
GRID    15              1.52777 4.7358  0.0
GRID    16              1.73926 5.5251  0.0
GRID    17              1.03528 0.0     0.0
GRID    18              1.24677 .7893   0.0
GRID    19              1.45826 1.5786  0.0
GRID    20              1.66975 2.3679  0.0
GRID    21              1.88124 3.1572  0.0
GRID    22              2.09273 3.9465  0.0
GRID    23              2.30422 4.7358  0.0
GRID    24              2.51572 5.5251  0.0
GRID    25              1.81173 0.0     0.0
GRID    26              2.02322 .7893   0.0
GRID    27              2.23471 1.5786  0.0
GRID    28              2.44621 2.3679  0.0
GRID    29              2.6577  3.1572  0.0
GRID    30              2.86919 3.9465  0.0
GRID    31              3.08068 4.7358  0.0
GRID    32              3.29217 5.5251  0.0
GRID    33              2.07055 0.0     0.0
GRID    34              2.28204 .7893   0.0
GRID    35              2.49353 1.5786  0.0
GRID    36              2.70502 2.3679  0.0
GRID    37              2.91652 3.1572  0.0
GRID    38              3.12801 3.9465  0.0
GRID    39              3.3395  4.7358  0.0
GRID    40              3.55099 5.5251  0.0
$                                                                       $
CQUAD4  1       1       1       2       10      9                       +M00000
+M00000                 .001    .001     .041    .041
CQUAD4  2       1       2       3       11      10                      +M00001
+M00001                 .001    .001     .041    .041
CQUAD4  3       1       3       4       12      11                      +M00002
+M00002                 .001    .001     .041    .041
CQUAD4  4       1       4       5       13      12                      +M00003
+M00003                 .001    .001     .041    .041
```

```
CQUAD4  5       1       5       6       14      13              +M00004
+M00004                 .001    .001    .041    .041
CQUAD4  6       1       6       7       15      14              +M00005
+M00005                 .001    .001    .041    .041
CQUAD4  7       1       7       8       16      15              +M00006
+M00006                 .001    .001    .041    .041
CQUAD4  8       1       9       10      18      17
CQUAD4  9       1       10      11      19      18
CQUAD4  10      1       11      12      20      19
CQUAD4  11      1       12      13      21      20
CQUAD4  12      1       13      14      22      21
CQUAD4  13      1       14      15      23      22
CQUAD4  14      1       15      16      24      23
CQUAD4  15      1       17      18      26      25
CQUAD4  16      1       18      19      27      26
CQUAD4  17      1       19      20      28      27
CQUAD4  18      1       20      21      29      28
CQUAD4  19      1       21      22      30      29
CQUAD4  20      1       22      23      31      30
CQUAD4  21      1       23      24      32      31
CQUAD4  22      1       25      26      34      33              +M00007
+M00007                 .041    .041    .001    .001
CQUAD4  23      1       26      27      35      34              +M00008
+M00008                 .041    .041    .001    .001
CQUAD4  24      1       27      28      36      35              +M00009
+M00009                 .041    .041    .001    .001
CQUAD4  25      1       28      29      37      36              +M00010
+M00010                 .041    .041    .001    .001
CQUAD4  26      1       29      30      38      37              +M00011
+M00011                 .041    .041    .001    .001
CQUAD4  27      1       30      31      39      38              +M00012
+M00012                 .041    .041    .001    .001
CQUAD4  28      1       31      32      40      39              +M00013
+M00013                 .041    .041    .001    .001
$                                                               $
PSHELL  1       1       .041    1               1
$                                                               $
CONVERT MASS    .0025901
$                                                               $
MFORM   COUPLED
$                                                               $
MAT1    1       6.3604+62.5442+6        .0626202
$                                                               $
SPC1    1       12345   9
SPC1    1       12345   25
SPC1    1       6       1       THRU    40
$                                                               $
ASET1   25      3       1       THRU    8
ASET1   25      3       10      THRU    24
ASET1   25      3       26      THRU    40
$                                                               $
EIGR    10      MGIV                            8               +ER
+ER     MAX
$                                                               $
$ * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * $
$                                                               $
$                       Z A E R O   I N P U T                   $
$                                                               $
$ * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * $
$                                                               $
$ THIS CASE DEMONSTRATES A SINGLE WING, HIGH SUPERSONIC FLUTTER CASE $
$ WITH AND WITHOUT WING THICKNESS EFFECTS (I.E. ZONA7 AND ZONA7U   $
$ METHODS, RESPECTIVELY) USING THE PK AND K FLUTTER SOLUTION METHODS. $
$                                                               $
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
$                                                               $
$                                                               $
$               * AERO PARAMETERS / FLIGHT CONDITIONS *         $
$                                                               $
$                                                               $
$       ACSID   XZSYM   RHOREF  REFC    REFB    REFS    GREF    $
AEROZ   0       YES     1.145-7 2.07055 1.      1.
$                                                               $
$                                                               $
$ TWO MKAEROZ BULK DATA CARDS ARE USED. THE FIRST MKAEROZ ACTIVATES THE $
$ LINEAR METHOD (ZONA7) AND THE SECOND THE NONLINEAR METHOD (ZONA7U)  $
$ VIA THE METHOD FLAG.  EACH MKAEROZ CARD IS REFERENCED BY A FLUTTER  $
$ CARD BELOW.                                                   $
$                                                               $
$       IDMK    MACH    METHOD  IDFLT   SAVE    <--FILENAME-->  PRINT   $
MKAEROZ 1000    3.0     0                                       0       +MK1
$       FREQ1   FREQ2   ETC                                             $
+MK1    0.0001  0.02    0.03    0.04    0.05    0.06    0.07    0.08
$                                                                       $
MKAEROZ 2000    3.0     1                                       0       +MK2
+MK2    0.0001  0.02    0.03    0.04    0.05    0.06    0.07    0.08
$                                                                       $
$                                                                       $
$                       * WING MACROELEMENT *                           $
$                                                                       $
$                                                                       $
$       WID     LABEL   ACOORD  NSPAN   NCHORD  LSPAN   ZTAIC   PAFOIL7 $
CAERO7  101     WING    0       11      9                       100     +CA101
$       XRL     YRL     ZRL     RCH     LRCHD   ATTCHR                  $
+CA101  0.0     0.0     0.0     2.07055 0       0                       +CA102
$       XRT     YRT     ZRT     TCH     LTCHD   ATTCHT                  $
+CA102  1.48044 5.52510 0.0     2.07055 0       0
```

```
$                                                                       $
$ THE PAFOIL7 CARD IS USED TO DEFINE THE AIRFOIL THICKNESS ALLOWING     $
$ FOR THE INPUT OF HALF THICKNESS, CAMBER AND LEADING EDGE RADII AT     $
$ THE WING ROOT AND TIP.  THICKNESS AND CAMBER DISTRIBUTIONS BETWEEN    $
$ THE WING ROOT AND TIP ARE INTERPOLATED. FOR THIS CASE, A 2% THICK     $
$ HEXAGONAL AIRFOIL SECTION IS DEFINED. A NEGATIVE VALUE OF ITAX        $
$ REQUESTS THAT A LINEAR INTERPOLATION BE USED FOR THICKNESS AND        $
$ CAMBER DISTRIBUTIONS (POSITIVE VALUE IS FOR CUBIC INTERPOLATION).     $
$ THICKNESS AND CAMBER DISTRIBUTIONS ARE USED ONLY FOR SUPERSONIC       $
$ THICKNESS EFFECTS (ZONA7U) WHEN THE 'METHOD' ENTRY IS ACTIVE IN       $
$ MKAEROZ BULK DATA CARD.                                               $
$                                                                       $
$       ID      ITAX    ITHR    ICAMR   RADR    ITHT    ICAMT   RADT    $
PAFOIL7 100     -101    102     103     0.0     102     103     0.0
$                                                                       $
$       SID     D1      D2      ETC
AEFACT  101     0.0     12.5    87.5    100.
AEFACT  102     0.0     1.0     1.0     0.0
AEFACT  103     0.0     0.0     0.0     0.0
$                                                                       $
$                                                                       $
$                  * SURFACE SPLINE FIT ON THE WING *                   $
$                                                                       $
$                                                                       $
$       EID     MODEL   CP      SETK    SETG    DZ      EPS             $
SPLINE1 100     WING            101     100     0.0
$                                                                       $
$       SETID   MACROID BOX1    BOX2    ETC                             $
PANLST2 101     101     101     THRU    180
$                                                                       $
$       SID     G1      G2      ETC                                     $
SET1    100     2       4       6       8       9       11      13      +S1
+S1     15      18      20      22      24      25      27      29      +S2
+S2     31      34      36      38      40
$                                                                       $
$                                                                       $
$                                                                       $
$                       * * FLUTTER ANALYSIS * *                        $
$                                                                       $
$                                                                       $
$ THE FLUTTER BULK DATA CARDS EMPLOY THE PK AND K FLUTTER SOLUTION      $
$ METHODS.  EACH FLUTTER CARD REFERS TO A DIFFERENT MKAEROZ BULK DATA   $
$ CARD.  THE FIRST FLUTTER CASE REFERS TO AN MKAEROZ CARD WITH AN IDMK  $
$ OF 1000 (WING WITHOUT THICKNESS CASE - ZONA7 AERODYNAMICS).  THE      $
$ SECOND FLUTTER CASE REFERS TO AN MKAEROZ CARD WITH IDMK = 2000        $
$ (WING WITH THICKNESS CASE - ZONA7U AERODYNAMICS).                     $
$                                                                       $
$         SETID METHOD  DENS    IDMK    VEL     MLIST   KLIST   EFFID   $
FLUTTER 30      PKK     1       1000    3                               +FL1
$         SYMXZ SYMXY   EPS     CURVFIT PRINT                           $
+FL1    1
$                                                                       $
FLUTTER 40      PKK     1       2000    3                               +FL2
+FL2    1
$                                                                       $
$       SID     F1      F2      ETC                                     $
FLFACT  1       .391
FLFACT  3       20000.  22000.  24000.  28000.  32000.  34000.
ENDDATA
```

2.4 Case 4: Sample Wing-Body-Tiptank Flutter Analysis

- ***Purpose:*** Demonstrate a subsonic and supersonic wing-body-tiptank flutter analysis case using the P-K and K methods.

- ***Description of Input:***

A wing-body-tiptank configuration is considered for the present case. The aerodynamic model of this configuration is shown in Fig 2.4.1.

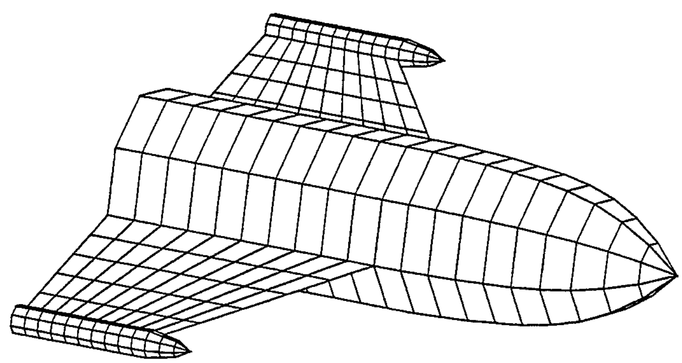


Figure 2.4.1 Aerodynamic Model of Sample Wing-Body-Tiptank Case.

- Solution Control

An analysis run is performed with the MODES and FLUTTER disciplines. The BOUNDARY condition specifies SPC = 10 that selects the single-point constraints for grid points, REDUCE = 30 that selects the analysis set degrees of freedom, and METHOD = 20 that selects the eigenvalue extraction method to be used. Two flutter cases are requested. The first FLCOND = 99 selects the subsonic (M = 0.8) flutter case and the second FLCOND = 100 selects the supersonic (M = 1.2) flutter case.

- Structural Model

A cropped delta wing with leading edge sweptback angle of 35.54° is used. The wing half-span and the root chord lengths are 70 inches and 100 inches, respectively. The wing is made of aluminum with a uniform thickness of 1.5 inches and is supported by an actuator at one third of the wing root. The aluminum wing is discretized into nine **CQUAD4** elements. The actuator is idealized by a **CBAR** element. Thus, the total number of grid points is seventeen. The **CBAR** is clamped at the grid point 20000, which is constrained for all six degrees of freedom. The cropped delta wing structural finite element (FEM) model is shown in Fig 2.4.2.

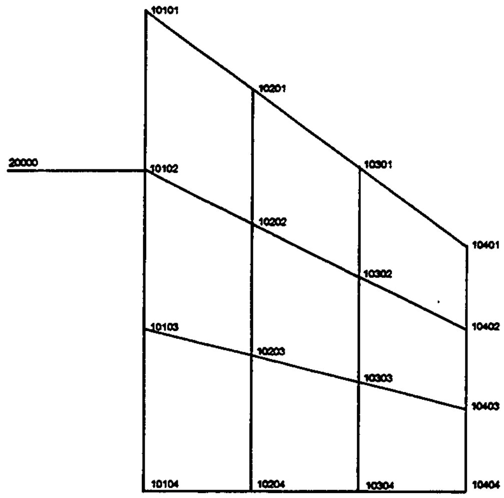


Figure 2.4.2 Cropped Delta Wing Structural Finite Element Model.

No structural FEM modeling is included for the body or tiptank in the present case. Spline of the tiptank to the wing is done via the **ATTACH** bulk data card, in which the rotational and displacement degrees of freedom are translated from a single grid point (i.e. grid no. 10402) to the entire tiptank. The fuselage, represented by a **BODY7** bulk data card, is not splined and, therefore, does not undergo any unsteady motion in this flutter analysis. However, body aerodynamics and wing-body aerodynamic interference (set via the ATTCHR/ATTCHT entries of the **CAERO7** bulk data card) are computed and accounted for in the analysis.

- *Aerodynamic Parameters / Flight Conditions*

The **AEROZ** bulk data card specifies a symmetric model about the x-z plane. A reference density of 1.145E-07 slinches (sea level density) and reference length of 100.0 inches are used.

Two **MKAEROZ** bulk data cards with IDMK's of 10 and 20 are used to specify freestream Mach numbers of 0.8 and 1.2, respectively. Eleven reduced frequencies are input ranging from 0.0001 to 0.55.

- *Aerodynamic Model*

One **CAERO7** wing macroelement is defined with 11 chordwise and 6 spanwise evenly cut aerodynamic boxes. Root and tip chord lengths are 100 and 50 inches, respectively, with a 100 inch semispan length. The wing root is attached to the fuselage body with the ATTCHR entry set to the fuselage **BODY7** bulk data card id (BID) of 201 to ensure proper treatment of the wing-body aerodynamic interference effects. Likewise, the wing tip is attached to the tiptank with the ATTCHT entry set to the tiptank **BODY7** bulk data card id (BID) of 401. Using the attachment option will avoid the wing root and tip from being treated as "free lifting surface edges" which will lead to incorrect unsteady pressure results in these regions.

The fuselage is defined by a **BODY7** macroelement with 5 circumferential and 21 axial cuts. The **BODY7** coordinates are specified within a local coordinate system defined by an **ACOORD** bulk data card with an ID of 20 located at (-100.0, 0.0, 0.0) that references the basic system (0.0, 0.0, 0.0). Fuselage cross-sections are specified through the body-of-revolution type of input (ITYPEi = 1 of the **SEGMESH** bulk data card) with camber and cross-sectional radius given at each of the 21 axial stations.

The tiptank is defined by a **BODY7** macroelement with 9 circumferential and 14 axial cuts. The **BODY7** coordinates are specified within a local coordinate system defined by an **ACOORD** bulk data card with an ID of 30 located at (35.0, 105.0, 0.0) that references the basic system (0.0, 0.0, 0.0). Fuselage cross-sections are specified through the body-of-revolution type of input (ITYPEi = 1 of the **SEGMESH** bulk data card) with camber and cross-sectional radius given at each of the 14 axial stations.

Note that the selection of wing and body macroelement id's (WID and BID) is not completely arbitrary. These integers must be selected so that no duplicate grid and/or aerodynamic box id's occur. For example, if a wing macroelement is set up with an id of 11 that has 10 x 10 aero box cuts and another wing macroelement is used with an id of 51, then duplicate grid and aero box id's will occur. This is because ZAERO establishes internal aero grid and box id's with starting values based on the macroelement id. Therefore, an aero box and grid with an id of 51 will already exist from the first macroelement (see the ASTROS* User's Manual for detailed description). In the present case, the first body macroelement (BID = 201) has 5 radial and 21 axial cuts. This will generate internally 105 (i.e. 21 x 5) aerodynamic grid points and 80 (i.e. (21-1) x (5-1)) aerodynamic boxes. Therefore, the next available macroelement id would be 307 (i.e. 201 + 105 + 1).

- *Spline*

A **SPLINE1** bulk data card is used to spline the aerodynamic wing model to the structure. A **PANLST2** bulk data card is referenced by the SETK = 102 entry and a **SET1** bulk data card by the SETG = 103 entry. The **PANLST2** defines the wing macroelement to be splined (**CAERO7** with WID of 101), and splines all of the wing aerodynamic boxes (101 through 150) to the structural grid points listed in the **SET1** bulk data card.

An **ATTACH** bulk data card is used to transfer the displacement and rotational motion of a reference **GRID** point (REFGRID = 10402) located at the wing tip to the tiptank. A **PANLST2** bulk data card is referenced by the SETK = 402 entry splines all of the tiptank aerodynamic boxes (401 through 540) to the reference grid point.

- *Flutter*

Two **FLUTTER** bulk data cards are used to perform two separate flutter analyses. The first **FLUTTER** bulk data card (SETID=99) refers to an **MKAEROZ** bulk data card (IDMK=10) with a Mach number of 0.8. The second **FLUTTER** bulk data card (SETID=100) refers to an **MKAEROZ** bulk data card (IDMK=20) with a Mach number of 1.2. The referenced **FLFACT** bulk data cards in entries DENS and VEL specify the density ratios and velocities for the P-K method, respectively. Both **FLUTTER** bulk data cards request that the P-K and K methods be used (METHOD entry set to PKK).

- ***Description of Output:***

The structural natural frequencies and generalized mass for the first five modes generated by the ASTROS* modal analysis is shown in Table 2.4.1.

Table 2.4.1 Natural Frequencies and Generalized Mass of the Wing-Body-Tiptank Case.

Mode No.	ASTROS* Natural Frequency (Hz)	ASTROS* Generalized Mass
1	4.461	4.36703E-01
2	10.556	3.02312E-01
3	29.392	2.70375E-01
4	32.566	9.04735E-02
5	50.038	4.82148E-01

- ***Subsonic Flutter Results (M=0.8)***

K-method flutter results of damping and frequency versus velocity for the first two modes are shown in Fig 2.4.3. The flutter crossing occur at $V_f = 956$ ft/s and $\omega_f = 7.92$ Hz.

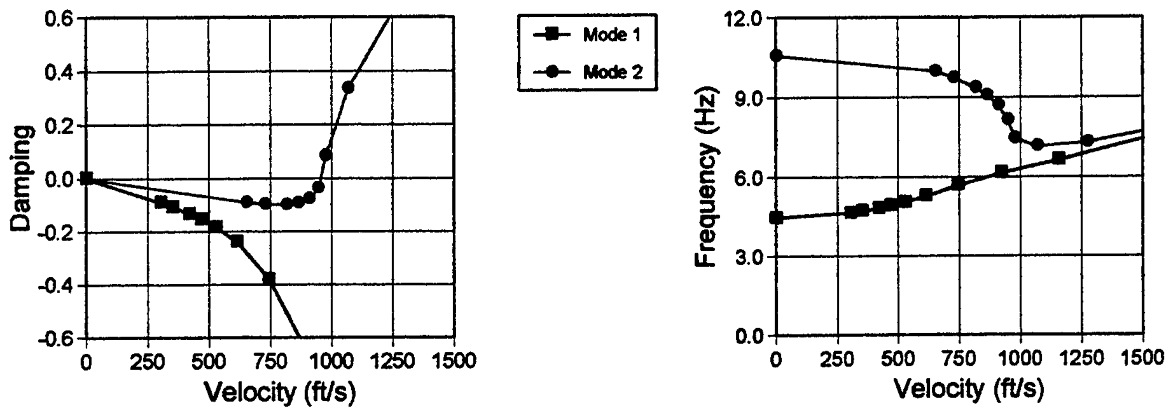


Figure 2.4.3 K-Method Flutter Curves of Wing-Body-Tiptank Case (M=0.8, Sea Level Density).

P-K method flutter results for this same case are shown in Fig 2.4.4. Flutter crossings occur at $V_f = 959$ ft/s and $\omega_f = 7.83$ Hz.

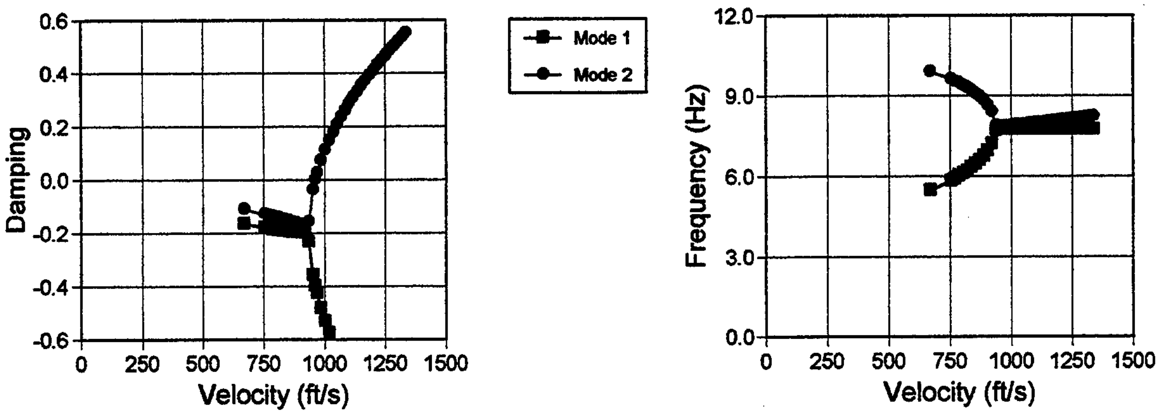


Figure 2.4.4 P-K Method Flutter Curves of Wing-Body-Tiptank Case (M=0.8, Sea Level Density).

- ***Spersonic Flutter Results (M=1.2)***

K-method flutter results of damping and frequency versus velocity for the first two modes are shown in Fig 2.4.5. The flutter crossing occur at $V_f = 1014$ ft/s and $\omega_f = 8.35$ Hz.

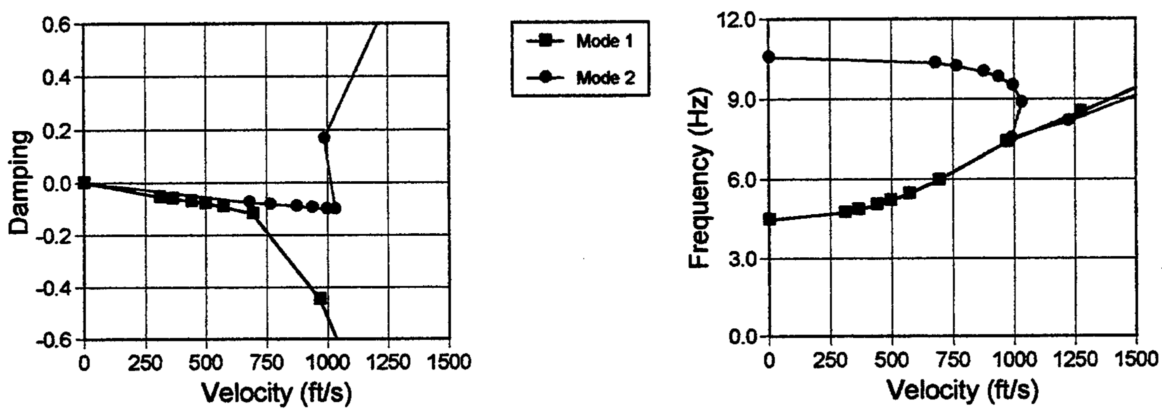


Figure 2.4.5 K-Method Flutter Curves of Wing-Body-Tiptank Case (M=1.2, Sea Level Density).

P-K method flutter results for this same case are shown in Fig 2.4.6. Flutter crossings occur at $V_f = 966$ ft/s and $\omega_f = 7.63$ Hz.

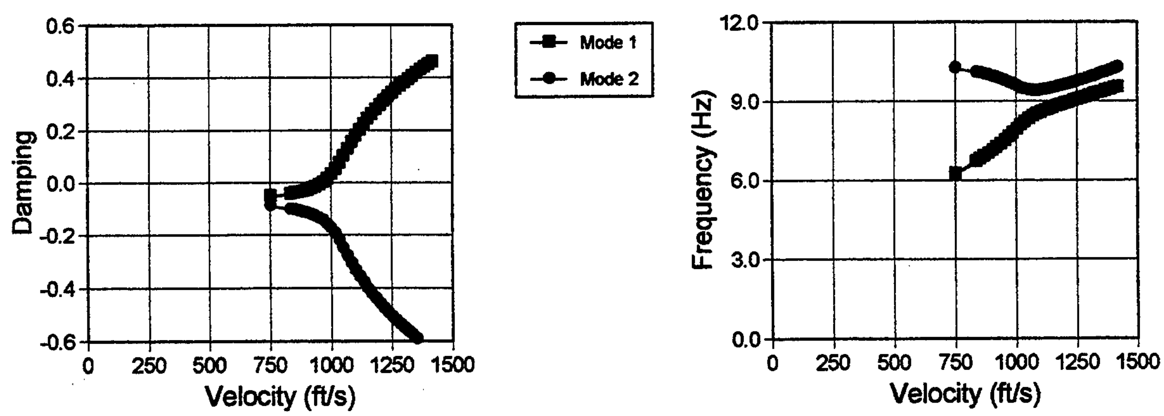


Figure 2.4.6 P-K Method Flutter Curves of Wing-Body-Tiptank Case (M=1.2, Sea Level Density).

Good agreement between the P-K and K-flutter methods are obtained for both Mach numbers. The larger discrepancy between the two methods for the supersonic case is due to the abrupt flutter point crossing in the K-method results (see Fig 2.4.5). Improved correlation can be obtained by increasing the number of reduced frequencies listed in the MKAEROZ bulk data card with IDMK=20 at the flutter point crossing (i.e. between k=0.2 and 0.225).

- ***Input Data Listing:***

Listing 2.4 Input Data for the Wing-Body-Tiptank Case.

```
ASSIGN DATABASE CROP PASS NEW DELETE
SOLUTION
    TITLE = SAMPLE WING-BODY-TIPTANK CASE
  ANALYZE
    BOUNDARY SPC=10, REDUCE=30, METHOD=20
        MODES
        PRINT ROOT = ALL
        LABEL = MODAL ANALYSIS
        FLUTTER (FLCOND=99)
        PRINT ROOT = ALL
        LABEL = SUBSONIC FLUTTER ANALYSIS
        FLUTTER (FLCOND=100)
        PRINT ROOT = ALL
        LABEL = SUPERSONIC FLUTTER ANALYSIS
END
$
BEGIN BULK
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
ASET1   30      3       10101   THRU    10104
ASET1   30      3       10201   THRU    10204
ASET1   30      3       10301   THRU    10304
ASET1   30      3       10401   THRU    10404
ASET1   30      45      10402
CBAR    1010    1010    10102   20000   10101
CQUAD4  1001    1000    10101   10102   10202   10201
CQUAD4  1002    1000    10102   10103   10203   10202
CQUAD4  1003    1000    10103   10104   10204   10203
CQUAD4  1004    1000    10201   10202   10302   10301
CQUAD4  1005    1000    10202   10203   10303   10302
CQUAD4  1006    1000    10203   10204   10304   10303
CQUAD4  1007    1000    10301   10302   10402   10401
CQUAD4  1008    1000    10302   10303   10403   10402
CQUAD4  1009    1000    10303   10304   10404   10403
EIGR    20      MGIV            5.0             5                       +ABC
+ABC    MAX
GRID    10101           0.0     30.000  0.0
GRID    10102           33.333  30.000  0.0
GRID    10103           66.667  30.000  0.0
GRID    10104           100.000 30.000  0.0
GRID    10201           16.667  53.333  0.0
GRID    10202           44.444  53.333  0.0
GRID    10203           72.222  53.333  0.0
GRID    10204           100.000 53.333  0.0
GRID    10301           33.333  76.667  0.0
GRID    10302           55.555  76.667  0.0
GRID    10303           77.778  76.667  0.0
GRID    10304           100.000 76.667  0.0
GRID    10401           50.000  100.000 0.0
GRID    10402           66.667  100.000 0.0
GRID    10403           83.333  100.000 0.0
GRID    10404           100.000 100.000 0.0
GRID    20000           33.333  0.0     0.0
MAT1    1100    1.E+07          .3      .1
CONVERT MASS    .00259
PBAR    1010    1100    100.    .1E+04  .1E+04  .05E+04
PSHELL  1000    1100    1.5     1100
SPC1    10      6       10101   THRU    10104
SPC1    10      6       10201   THRU    10204
SPC1    10      6       10301   THRU    10304
SPC1    10      6       10401   THRU    10404
SPC     10      20000   123456
$                                                                       $
$ * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * $
$                                                                       $
$                       Z A E R O    I N P U T                          $
$                                                                       $
$ * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * $
$                                                                       $
$ THIS CASE DEMONSTRATES A SUBSONIC + SUPERSONIC WING-BODT-TIPTANK      $
$ FLUTTER ANALYSIS CASE USING THE PK AND K FLUTTER SOLUTION METHODS.   $
$                                                                       $
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
$                                                                       $
```

```
$                                                                       $
$                     * AERO PARAMETERS / FLIGHT CONDITIONS *           $
$                                                                       $
$                                                                       $
$       ACSID   XZSYM   RHOREF  REFC    REFB    REFS    GREF            $
AEROZ           YES     1.145-07100.
$                                                                       $
$                                                                       $
$ TWO MKAEROZ CARDS ARE USED.  THE FIRST ACTIVATES THE SUBSONIC METHOD  $
$ (ZONA6) AND THE SECOND THE SUPERSONIC METHOD (ZONA7) - BASED ON THE   $
$ INPUT MACH NUMBER.                                                    $
$                                                                       $
$       IDMK    MACH    METHOD  IDFLT   SAVE    <--FILENAME-->  PRINT   $
MKAEROZ 10      0.8     0               ACQUIRE CROPAIC                 +MK1
$       FREQ1   FREQ2   ETC                                             $
+MK1    0.001   0.1     0.15    0.175   0.2     0.225   0.25    0.275   +MK1
+MK1    0.3     0.35    0.4
$                                                                       $
MKAEROZ 20      1.2     0               ACQUIRE CROPAIC                 +MK1
+MK1    0.001   0.1     0.15    0.175   0.2     0.225   0.25    0.275   +MK1
+MK1    0.3     0.35    0.4
$                                                                       $
$                                                                       $
$                           * WING MACROELEMENT *                       $
$                                                                       $
$                                                                       $
$       WID     LABEL   ACOORD  NSPAN   NCHORD  LSPAN   ZTAIC   PAFOIL7 $
CAERO7  101     WING            6       11                              +CA1
$       XRL     YRL     ZRL     RCH     LRCHD   ATTCHR                  $
+CA1    0.0     30.0    0.0     100.0   0       201                     +CA2
$       XRT     YRT     ZRT     TCH     LTCHD   ATTCHT                  $
+CA2    50.0    100.0   0.0     50.0    0       401
$                                                                       $
$                                                                       $
$                           * BODY MACROELEMENT *                       $
$                                ( FUSELAGE )                           $
$                                                                       $
$                                                                       $
$ TWO BODY7 BULK DATA CARDS ARE USED TO DEFINE THE FUSELAGE AND TIPTANK $
$ MACROELEMENTS.  EACH BODY7 COORDINATES ARE BASED ON A LOCAL COORDINATE$
$ SYSTEM SPECIFIED BY THE ACCORD BULK DATA ENTRIES.  THE BODY-OF-       $
$ REVOLUTION TYPE OF INPUT IS USED FOR BOTH THE FUSELAGE AND TIPTANK    $
$ TO SPECIFY THE CROSS-SECTIONAL RADIUS AND CAMBER (SEGMESH BULK DATA   $
$ CARD).
$                                                                       $
$ COORDINATE SYSTEM FOR FUSELAGE                                        $
$       ID      XORIGN  YORIGN  ZORIGN  DELTA   THETA                   $
ACOORD  20      -100.   0.0     0.0     0.0     0.0
$                                                                       $
$       BID     LABEL   IPBODY7 ACOORD  NSEG    IDMESH1 IDMESH2 ETC     $
BODY7   201     FUSELAGE        20      1       201
$                                                                       $
$       IDMESH  NAXIS   NRAD                                            $
SEGMESH 201     21      5                                               +SE1
$       ITYPE   X1      CAM1    YR1     ZR1     IDY1    IDZ1            $
+SE1    1       0.0     0.0     0.0                                     +SE2
+SE2    1       10.0    0.0     10.0                                    +SE3
+SE3    1       20.0    0.0     17.0                                    +SE4
+SE4    1       30.0    0.0     22.0                                    +SE5
+SE5    1       40.0    0.0     25.0                                    +SE6
+SE6    1       50.0    0.0     27.0                                    +SE7
+SE7    1       60.0    0.0     28.0                                    +SE8
+SE8    1       70.0    0.0     29.0                                    +SE9
+SE9    1       80.0    0.0     29.5                                    +SE10
+SE10   1       90.0    0.0     30.0                                    +SE11
+SE11   1       100.0   0.0     30.0                                    +SE12
+SE12   1       110.0   0.0     30.0                                    +SE13
+SE13   1       120.0   0.0     30.0                                    +SE14
+SE14   1       130.0   0.0     30.0                                    +SE15
+SE15   1       140.0   0.0     30.0                                    +SE16
+SE16   1       150.0   0.0     30.0                                    +SE17
+SE17   1       160.0   0.0     30.0                                    +SE18
+SE18   1       170.0   0.0     30.0                                    +SE19
+SE19   1       180.0   0.0     30.0                                    +SE20
+SE20   1       190.0   0.0     30.0                                    +SE21
+SE21   1       200.0   0.0     30.0
$                                                                       $
$                                                                       $
$                           * BODY MACROELEMENT *                       $
$                                 ( TIPTANK )                           $
$                                                                       $
$                                                                       $
$ COORDINATE SYSTEM FOR TIPTANK                                         $
$       ID      XORIGN  YORIGN  ZORIGN  DELTA   THETA                   $
ACOORD  30      35.0    105.0   0.0     0.0     0.0
$                                                                       $
$       BID     LABEL   IPBODY7 ACOORD  NSEG    IDMESH1 IDMESH2 ETC     $
BODY7   401     TIPTANK         30      1       401
$                                                                       $
$       IDMESH  NAXIS   NRAD                                            $
SEGMESH 401     14      9                                               +SE1
$       ITYPE   X1      CAM1    YR1     ZR1     IDY1    IDZ1            $
+SE1    1       0.0     0.0     0.0                                     +SE2
+SE2    1       5.0     0.0     3.0                                     +SE3
+SE3    1       10.0    0.0     4.0                                     +SE4
+SE4    1       15.0    0.0     5.0                                     +SE5
+SE5    1       20.0    0.0     5.0                                     +SE6
```

```
+SE6    1       25.0    0.0     5.0                                             +SE7
+SE7    1       30.0    0.0     5.0                                             +SE8
+SE8    1       35.0    0.0     5.0                                             +SE9
+SE9    1       40.0    0.0     5.0                                             +SE10
+SE10   1       45.0    0.0     5.0                                             +SE11
+SE11   1       50.0    0.0     5.0                                             +SE12
+SE12   1       55.0    0.0     5.0                                             +SE13
+SE13   1       60.0    0.0     5.0                                             +SE14
+SE14   1       65.0    0.0     5.0
$
$                                                                               $
$                                                                               $
$                      * SURFACE SPLINE FIT ON THE WING *                       $
$                                                                               $
$                                                                               $
$       EID     MODEL   CP      SETK    SETG    DZ      EPS                     $
SPLINE1 101     WING            102     103     0.0     0.01
$                                                                               $
$       SETID   MACROID BOX1    BOX2    ETC                                     $
PANLST2 102     101     101     THRU    150
$                                                                               $
$       SID     G1      G2      ETC                                             $
SET1    103     10101   10102   10103   10104   10201   10202   10203   +SE1
+SE1    10204   10301   10302   10303   10304   10401   10402   10403   +SE2
+SE2    10404
$                                                                               $
$                                                                               $
$                       * TIPTANK TO WING ATTACHMENT *                          $
$                                                                               $
$                                                                               $
$ THE ATTACH BULK DATA CARD TRANSFERS THE DISPLACEMENT AND ROTATIONAL           $
$ MOTION OF A REFERENCE GRID POINT TO AN AERODYNAMIC BOX(ES).  IN THIS          $
$ CASE, ALL OF THE TIPTANK AERO BOXES (401 THRU 504) WILL FOLLOW THE            $
$ MOTIONS OF THE REFERENCE GRID POINT (GRID 10402) LOCATED AT THE WING          $
$ TIP.                                                                          $
$                                                                               $
$       EID     MODEL   SETK    REFGRID                                         $
ATTACH  401             402     10402
$                                                                               $
$       SETID   MACROID BOX1    BOX2    ETC                                     $
PANLST2 402     401     401     THRU    504
$                                                                               $
$                                                                               $
$                           * FLUTTER ANALYSIS *                                $
$                                                                               $
$                                                                               $
$       SETID   METHOD  DENS    IDMK    VEL     MLIST   KLIST   EFFID           $
FLUTTER 99      PKK     101     10      102                                     +FL1
$       SYMXZ   SYMXY   EPS     CURVFIT PRINT                                   $
+FL1    1
$                                                                               $
$       SID     F1      F2      ETC                                             $
FLFACT  101     1.0
FLFACT  102     8000.   9000.   10000.  11000.  12000.  13000.  14000.  +FL1
+FL1    15000.  16000.
$                                                                               $
FLUTTER 100     PKK     101     20      103                                     +FL1
+FL1    1
$                                                                               $
FLFACT  103     9000.   10000.  11000.  12000.  13000.  14000.  15000.  +FL1
+FL1    16000.  17000.
$                                                                               $
$                                                                               $
ENDDATA
```

2.5 Case 5: AGARD Standard 445.6 Wing – Transonic Flutter Analysis

- ***Purpose:*** Demonstrate a transonic wing flutter analysis case using the ZTAIC method with steady pressure input provided by CFD.

- ***Description of Input:***

The AGARD Standard 445.6 Weakened (modified AGARD Test Case from the ASTROS Application Manual (AFWAL-TR-88-3028), also AGARD Report No. 765, and NASA TN D-1616) is considered in the present case for both subsonic and transonic Mach numbers (M=0.678, 0.90, 0.95). The wing is a 45 degree swept-back wing of aspect ratio 6 with a NASA 64A004 airfoil section. The ZONA6 (linear) and ZTAIC (nonlinear) method flutter results are compared with wind tunnel measurement data. The ZTAIC method (ZAERO's transonic method) wing sectional steady pressure input used in the present analysis are obtained by two Computational Fluid Dynamics (CFD) codes: the CAPTSD (2D Euler) and ENSAERO (3D Navier-Stokes) codes. Similar to the AGARD Test Case presented in the ASTROS Applications Manual, the structural finite element model of this wing is replaced by the input of mode shapes, generalized mass and stiffness matrices of the first five modes via the Direct Matrix Input (DMI) bulk data. The aerodynamic model of the AGARD Standard 445.6 Wing is shown in Fig 2.5.1.

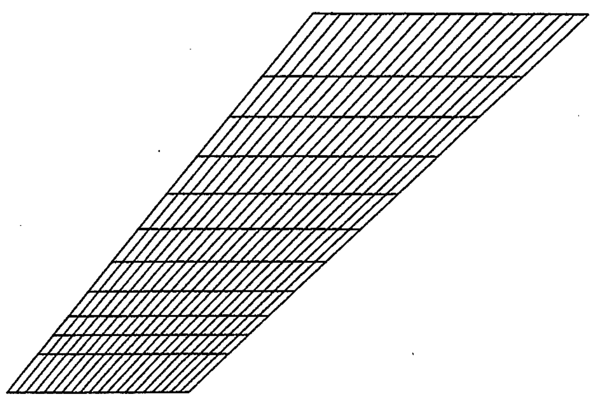


Figure 2.5.1 Aerodynamic Model of the AGARD Standard 445.6 Wing.

The natural frequencies and mode shapes of the weakened wing structure are presented in Fig 2.5.2. The dashed line wings represent the undeformed wing structure.

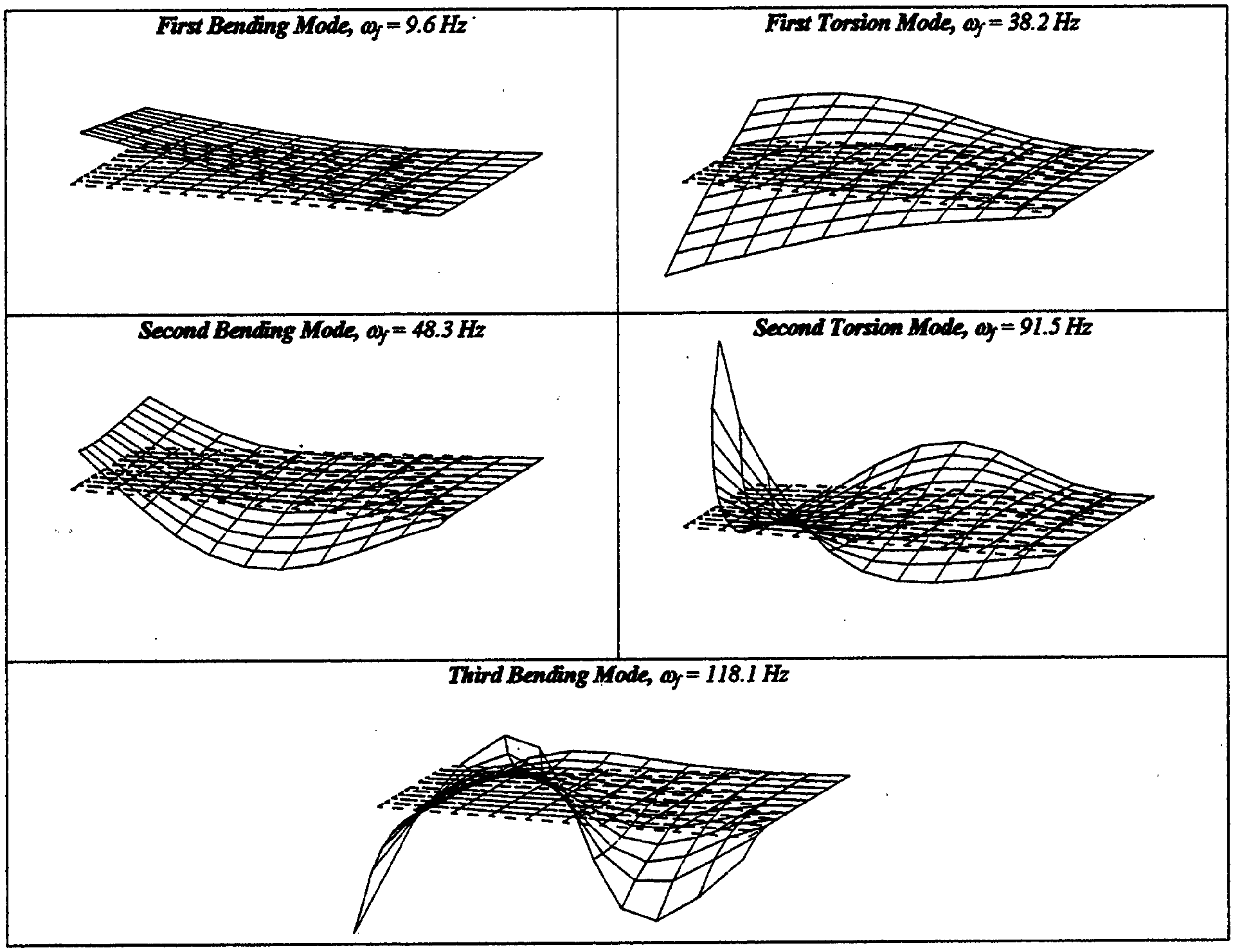


Figure 2.5.2 AGARD Standard 445.6 Weakened Wing Natural Frequencies and Mode Shapes (1st 5 modes).

For the present test case, wing sectional steady pressure input data is provided for all three Mach numbers. Steady pressure can be obtained by physical flight test data, wind tunnel data or by computational means (such as CFD). Accuracy of the ZTAIC method flutter results depends on the accuracy of the steady pressure input (i.e. ideal steady pressure input would come from flight test or wind tunnel measurement).

Differences in steady pressure input obtained by different sources (in this case 2 CFD codes) is shown in the following figure. The ZTAIC steady pressure input for Mach 0.95 and Angle-of-Attack (α) = 0°, used in the present case, as computed by the CAPTSD (Euler) and ENSAERO (Navier-Stokes) codes at 6 spanwise stations is shown in Fig 2.5.3.

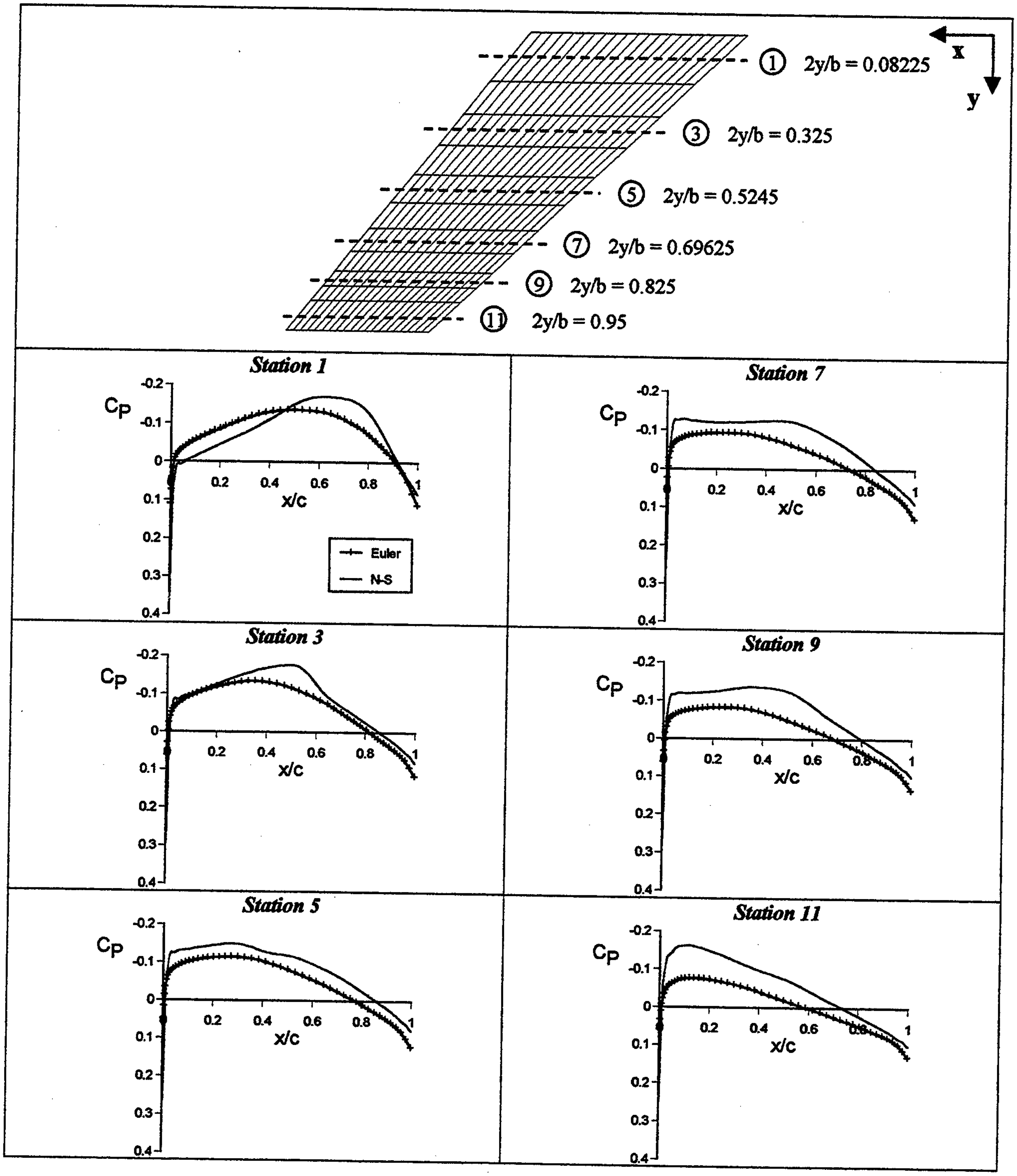


Figure 2.5.3 AGARD Standard 445.6 Weakened Wing CAPTSD (Euler) and ENSAERO (Navier-Stokes = N-S) Steady Pressure Results (M=0.95, α=0.0°).

Differences in terms of shock strength and location is seen between the Euler and Navier-Stokes results. The effect of these differences on the ZTAIC method flutter results is shown in the Description of Output section of the present case.

- Solution Control

Substantial modification to the ASTROS* standard Matrix Analysis Problem Oriented Language (MAPOL) sequence is implemented through the EDIT command. The optimization and global matrix assembly phases are deleted from the sequence. A modified flutter analysis routine is inserted omitting the dynamic matrix assembly to replace the standard flutter sequence.

An analysis is performed with six flutter subcases. The first case performs a ZTAIC (nonlinear) flutter analysis and the second a ZONA6 (linear) flutter analysis. This is repeated three times for each Mach number (M = 0.678, 0.90, 0.95).

- Structural Model

Structural model processing is replaced in this case by the mode shape, stiffness matrix and mass matrix input via the Direct Matrix Input (**DMI**) bulk data. Therefore, the ASTROS* structural input consists only of 121 grid points, all constrained in 5 degrees-of-freedom (DOF) with the 6th DOF (i.e. the z-translation) left free. This corresponds to 121 DOF for each mode. Five modes with corresponding natural frequencies are input by **DMI**'s. The mass matrix is a 5 x 5 identity matrix while the stiffness matrix is a diagonal matrix whose nonzero entries are the input eigenvalues.

- Aerodynamic Parameters / Flight Conditions

The **AEROZ** bulk data card specifies a symmetric model about the x-z plane. A reference density of 1.145E-07 slinches (sea level density) and reference length of 21.96 inches are used.

Six **MKAEROZ** bulk data cards are used to specify freestream Mach numbers of 0.678, 0.90 and 0.95 for both the linear (ZONA6) on nonlinear (ZTAIC) aerodynamic methods. Identical reduced frequencies ranging from 0.0001 to 0.5 are computed for all **MKAEROZ**.

The Aerodynamic Influence Coefficient (AIC) matrices associated with each **MKAEROZ** bulk data card are saved in filenames specified in the FILENAME entries. Mnemonic notation used for filenames consist of: Wing Name + Mach Number + Method Used. For example, 'AGARD678ZT' would be the AGARD wing at Mach 0.678 with the ZTAIC method used (i.e. METHOD entry set to 1 = nonlinear method).

- Aerodynamic Model

One wing macroelement is used to define the wing planform. 20 chordwise (evenly cut) and 11 spanwise (cuts specified in **AEFACT** bulk data card with SID=10) aerodynamic boxes are used. For the ZTAIC method to be "active" for this wing macroelement, the ZTAIC entry is set to 1001, which refers to a **ZTAIC** bulk data card that establishes the steady pressure input to be used on this wing.

- Spline

The infinite plate spline method (**SPLINE1**) is used to spline all of the wing aerodynamic boxes to the structural grid points. A **SPLINE1** bulk data card is used to spline the aerodynamic wing model to the structure. A **PANLST2** bulk data card is referenced by the SETK = 10 entry and a **SET1** bulk data card by the SETG =603 entry. The **PANLST2** defines the wing macroelement to be splined (**CAERO7** with WID of 1001), and splines all of the wing aerodynamic boxes (1001 through 1220) to the structural grid points listed in the **SET1** bulk data card (grids 1 through 121).

- Flutter

Six **FLUTTER** bulk data cards are input corresponding to each FLUTTER subcase specified in the solution control. The P-K and K methods of flutter solution are requested for all cases (METHOD entry set to PKK). Density ratios specified in the DENS entries refer to FLFACT bulk data cards which list density ratios that encompass the flutter matched point altitudes. IDMK entries refer to **MKAEROZ** bulk data cards that specify the Mach number/reduced frequencies for the flutter analysis. The same velocities for the P-K method are used for all flutter analyses (velocities listed in **FLFACT** bulk data card with SID=40).

- ZTAIC Method Steady Pressure Input

Transonic data for the ZTAIC method is input via the **ZTAIC**, **MACHCP** and **CHORDCP** bulk data entries. Only one set of steady pressure input can be used per ASTROS* run (i.e. either from wind tunnel measurement, Euler Code, N-S Code, etc.). Therefore, the **CHORDCP** bulk data used to input the steady pressure for all three Mach numbers of this case are saved in two separate files ('tsdcp.inp' for CAPTSD/Euler and 'nscp.inp' for ENSAERO/Navier-Stokes steady pressure) and are included in the bulk data input via the ASTROS **INCLUDE** statement (see ASTROS User's Manual for details on the **INCLUDE** statement). The user can select the desired pressure input by uncommenting the corresponding **INCLUDE** statement (by removing the $).

The ZTAIC bulk data card refers to 3 **MACHCP** bulk data cards that establish the Mach number and steady pressure input relations. Span locations and corresponding steady pressure for each section are specified by the SPANID and CHDCP entries, respectively.

For example, the **MACHCP** with ID of 1001 specifies a Mach number of 0.678. This Mach number <u>must</u> identically exist in on the the **MKAEROZ** bulk data cards with the nonlinear method "active" (i.e. METHOD entry set to 1). The spanwise station indicies (SPANID entries) correspond to the wing macroelement span division centerline locations. In this case an **AEFACT** bulk data card with ID=10 was used to specify the spanwise wing macroelement cuts. Therefore, the SPANID=1 refers to the wing span location of 8.22% ([0.0+16.45]/2), SPANID=2 refers to the wing span location of 21.85% ([16.45+27.25]/2), and so on.

CHORDCP entries in the 'tsdcp.inp' and 'nscp.inp' files contain the x-location of the pressure in percent chord length (X entries), the upper surface steady pressure coefficients (CPU entries), and the lower surface steady pressure coefficients (CPL entries).

- ***Description of Output:***

A matched point flutter analysis is performed to compare with wind tunnel data provided in the following reference, Yates, E.C., Jr., Land, M.S. and Foughner, J.T., Jr., "Measured and Calculated Subsonic and Transonic Flutter Characteristics of a 45° Sweptback Wing Planform in Air and Freon-12 in the Langley Transonic Dynamics Tunnel," NASA TN D-1616, March 1963.

The weakened wing model (model 3) is considered for this case with a span of 2.5 feet. The measured modal frequencies and panel mass for this wing are given in Table 2.5.1

Table 2.5.1 Measured Modal Frequencies and Panel Mass of the AGARD Standard 445.6 Weakened Wing Model.

Model Description				Frequency (Hz)					Panel mass, slugs
Panel span, ft	Mounting	Structure	Model	$f_{h,1}$	$f_{h,2}$	$f_{t,1}$	$f_{t,2}$	f_{α}	m
2.50	Wall	Weakened	3	9.60	50.70	38.10	98.50	38.09	0.12764

Table 2.5.2 presents the computed matched point density and mass ratios for the present case. The flutter matched point is found by varying the ASTROS* density ratios (specified in the FLFACT bulk data cards SID's=301-306) so that the computed speed of sound (i.e. computed flutter velocity divided by the input Mach number) matches that of the wind tunnel test results.

Table 2.5.2 Computed Density and Mass Ratios of the AGARD Standard 445.6 Wing.

	ZONA6		ZTAIC(TSD)		ZTAIC (N-S)		Experiment	
Mach	ρ/ρ_{SL}	μ	ρ/ρ_{SL}	μ	ρ/ρ_{SL}	μ	ρ/ρ_{SL}	μ
0.678	0.184	61.52	0.190	63.53	0.186	62.85	0.170	68.75
0.90	0.084	146.12	0.080	139.16	0.074	157.96	0.081	143.92
0.95	0.066	198.13	0.059	177.12	0.052	224.80	0.052	225.82

ρ/ρ_{SL}=density ratio, ρ_{SL}=sea level density, μ = mass ratio, Experimental data from NASA TN D-1616 (March 1963)

The mass ratio $\mu = m / (\rho V)$ is defined as the mass of the wing divided by the mass of air contained within the volume of a conical frustrum having the streamwise root chord as the lower base diameter, streamwise tip chord as the upper base diameter, and wing panel span as the height.

Table 2.5.3 presents the flutter frequency ratios and flutter speed coefficients for the present case.

Table 2.5.3 Computed Density and Mass Ratios of the AGARD Standard 445.6 Wing.

	ZONA6		ZTAIC(TSD)		ZTAIC (N-S)		Experiment	
Mach	$\frac{\omega}{\omega_\alpha}$	$\frac{U}{b_s\omega_\alpha\sqrt{\mu}}$	$\frac{\omega}{\omega_\alpha}$	$\frac{U}{b_s\omega_\alpha\sqrt{\mu}}$	$\frac{\omega}{\omega_\alpha}$	$\frac{U}{b_s\omega_\alpha\sqrt{\mu}}$	$\frac{\omega}{\omega_\alpha}$	$\frac{U}{b_s\omega_\alpha\sqrt{\mu}}$
0.678	0.5280	0.4343	0.5340	0.4399	0.5314	0.4363	0.4712	0.4174
0.90	0.4297	0.3754	0.4240	0.3666	0.4136	0.3522	0.4216	0.3700
0.95	0.3945	0.3460	0.3840	0.3276	0.3697	0.3068	0.3673	0.3059

Experimental data from NASA TN D-1616 (March 1963)

where ω is the flutter frequency, ω_α is the natural circular frequency of the wing in first uncoupled torsion mode ($2\pi f_\alpha$), **U** is the flutter velocity and $\mathbf{b_s}$ is the streamwise semichord measured at the wing root ($\mathbf{b_s}$=0.9165 feet).

Figure 2.5.4 presents the flutter flutter speed coefficients and frequency ratios of Table 2.5.3. At the subsonic Mach number of 0.678, the ZTAIC results are in close agreement with those of ZONA6, as expected, since transonic effects (such as shock wave) are minimum or nonexistent. At transonic Mach numbers, the ZTAIC results predicts a pronounced transonic dip that is not observed in the linear (ZONA6) results. Better correlation of flutter speed coefficient with experimental results is seen at Mach 0.95 for the ZTAIC case with Navier-Stokes (N-S) pressure input. This is expected since the N-S results account for fluid viscosity, thereby giving better predictions of shock poisition and strength.

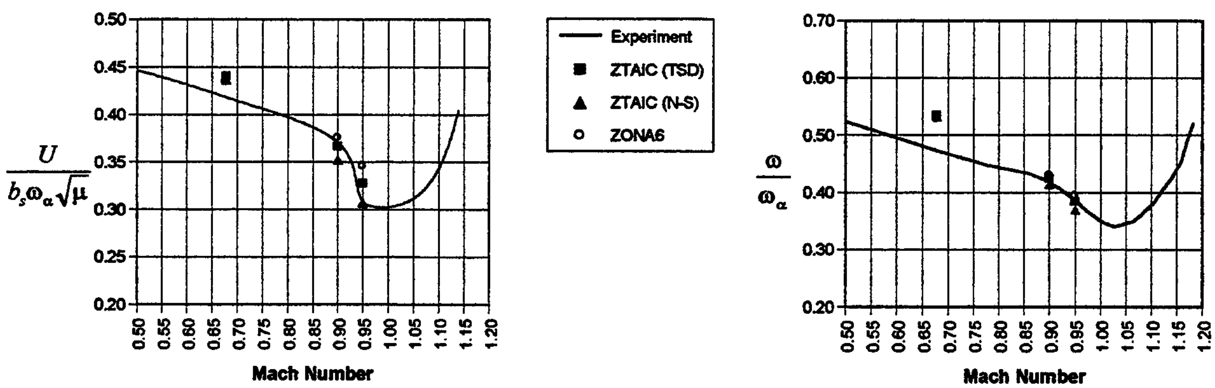


Figure 2.5.4 Plots of Flutter Speed Coefficients and Frequency Ratios of the AGARD Standard 445.6 Weakened Wing (matched point analysis).

- ***Input Data Listing:***

Listing 2.5 Input Data for the AGARD Standard 445.6 Wing (Weakened Model).

```
ASSIGN DATABASE AGARD PASS NEW DELETE
EDIT NOLIST
INSERT 3
$ ***
  *** EDIT:          (MAPOLSEQ VERSION 11.1)
  ***  TESTCASE DEMONSTRATING FLUTTER ANALYSIS WITH
  ***  DIRECT-INPUT OF MODE SHAPES AND FREQUENCIES.
```

```
  ***                                                                        $
MATRIX [MODES], [KFLUT];
REPLACE 371,1958
$ ***
  *** EDIT:
  ***  DELETE OPTIMIZATION PHASE.
  ***                                  $
REPLACE 1974,1975
$ ***
  *** EDIT:
  ***  DELETE GLOBAL MATRIX ASSEMBLY (EMA2).
  ***                                             $
REPLACE 2018,2746
$ ***
  *** EDIT:
  ***  REPLACE MATRIX REDUCTIONS, ANALYSIS SEGMENT AND DATA RECOVERY
  ***          WITH SPECIAL FLUTTER ANALYSIS
  ***                OMITTING DYNAMIC MATRIX ASSEMBLY (FLUTDMA).
  ***                                                                      $
     CALL NREDUCE ( , [UGTKG], [PNSF(BC)], , , , , [UGTKA] );
     PRINT("LOG=('         >>>DISCIPLINE: NORMAL MODES')");
     CALL REIG ( , BC, USET(BC), [KAA], [MAA], , , LAMBDA,
                 [PHIA], [MII], HSIZE(BC) );
     PRINT("LOG=('         >>>DISCIPLINE: FLUTTER')");
     CALL FLUTQHHZ ( , BC, SUB, ESIZE(BC), PSIZE(BC), [AJK],
                      [SKJ], [UGTKA], [MODES], USET(BC),
                      [TMN(BC)], [GSUBO(BC)], NGDR, AECOMPU, GEOMUA,
                      [PHIKH], [QHHLFL(BC,SUB)], OAGRDDSP );
     PRINT("LOG=('         >>>DISCIPLINE: FLUTTRAZ    ')");
     PRINT("LOG=('         >>>DISCIPLINE: FLUTTRAZ    ')");
       CALL FLUTTRAZ ( , BC, SUB, [QHHLFL(BC,SUB)], LAMBDA, HSIZE(BC),
                      ESIZE(BC), [MAA], [BHHFL(BC,SUB)],
                      [KFLUT], CLAMBDA, ,AEROZ );
SOLUTION
TITLE = AGARD STANDARD 445.6 WING TEST CASE USING THE ZTAIC (TRANSONIC) METHOD
SUBTITLE = WEAKENED WING (MODEL 3) - AGARD RPT. NO. 765
ANALYZE
   PRINT (MODE = ALL) ROOT = ALL
   BOUNDARY METHOD = 10
     MODES
       LABEL = WEAKENED MODES
     FLUTTER (FLCOND = 1)
       LABEL = ZTAIC (M=0.678) FLUTTER RESULTS
     FLUTTER (FLCOND = 2)
       LABEL = ZONA6 (M=0.678) FLUTTER RESULTS
     FLUTTER (FLCOND = 3)
       LABEL = ZTAIC (M=0.9) FLUTTER RESULTS
     FLUTTER (FLCOND = 4)
       LABEL = ZONA6 (M=0.9) FLUTTER RESULTS
     FLUTTER (FLCOND = 5)
       LABEL = ZTAIC (M=0.95) FLUTTER RESULTS
     FLUTTER (FLCOND = 6)
       LABEL = ZONA6 (M=0.95) FLUTTER RESULTS
END
BEGIN BULK
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
$                                                                        $
GRID    1               0.0     0.0     0.0             12456
GRID    2               2.196   0.0     0.0             12456
GRID    3               4.392   0.0     0.0             12456
GRID    4               6.588   0.0     0.0             12456
GRID    5               8.784   0.0     0.0             12456
GRID    6               10.75   0.0     0.0             12456
GRID    7               13.17   0.0     0.0             12456
GRID    8               15.37   0.0     0.0             12456
GRID    9               17.56   0.0     0.0             12456
GRID    10              19.76   0.0     0.0             12456
GRID    11              21.96   0.0     0.0             12456
$                                                                        $
GRID    12              3.1866  3.0     0.0             12456
GRID    13              5.3079  3.0     0.0             12456
GRID    14              7.4293  3.0     0.0             12456
GRID    15              9.5506  3.0     0.0             12456
GRID    16              11.672  3.0     0.0             12456
GRID    17              13.650  3.0     0.0             12456
GRID    18              15.914  3.0     0.0             12456
GRID    19              18.036  3.0     0.0             12456
GRID    20              20.157  3.0     0.0             12456
GRID    21              22.278  3.0     0.0             12456
GRID    22              24.400  3.0     0.0             12456
$                                                                        $
GRID    23              6.3732  6.0     0.0             12456
GRID    24              8.4199  6.0     0.0             12456
GRID    25              10.466  6.0     0.0             12456
GRID    26              12.513  6.0     0.0             12456
GRID    27              14.560  6.0     0.0             12456
GRID    28              16.600  6.0     0.0             12456
GRID    29              18.653  6.0     0.0             12456
GRID    30              20.700  6.0     0.0             12456
GRID    31              22.744  6.0     0.0             12456
GRID    32              24.793  6.0     0.0             12456
GRID    33              26.840  6.0     0.0             12456
$                                                                        $
GRID    34              9.5598  9.0     0.0             12456
GRID    35              11.531  9.0     0.0             12456
GRID    36              13.504  9.0     0.0             12456
GRID    37              15.476  9.0     0.0             12456
```

```
GRID    38              17.448  9.0     0.0             12456
GRID    39              19.500  9.0     0.0             12456
GRID    40              21.392  9.0     0.0             12456
GRID    41              23.364  9.0     0.0             12456
GRID    42              25.336  9.0     0.0             12456
GRID    43              27.308  9.0     0.0             12456
GRID    44              29.280  9.0     0.0             12456
$                                                               $
GRID    45              12.746  12.0    0.0             12456
GRID    46              14.643  12.0    0.0             12456
GRID    47              16.541  12.0    0.0             12456
GRID    48              18.438  12.0    0.0             12456
GRID    49              20.336  12.0    0.0             12456
GRID    50              22.300  12.0    0.0             12456
GRID    51              24.131  12.0    0.0             12456
GRID    52              26.028  12.0    0.0             12456
GRID    53              27.925  12.0    0.0             12456
GRID    54              29.823  12.0    0.0             12456
GRID    55              31.720  12.0    0.0             12456
$                                                               $
GRID    56              15.933  15.0    0.0             12456
GRID    57              17.755  15.0    0.0             12456
GRID    58              19.578  15.0    0.0             12456
GRID    59              21.401  15.0    0.0             12456
GRID    60              23.224  15.0    0.0             12456
GRID    61              25.200  15.0    0.0             12456
GRID    62              26.869  15.0    0.0             12456
GRID    63              28.692  15.0    0.0             12456
GRID    64              30.515  15.0    0.0             12456
GRID    65              32.338  15.0    0.0             12456
GRID    66              34.161  15.0    0.0             12456
$                                                               $
GRID    67              19.119  18.0    0.0             12456
GRID    68              20.867  18.0    0.0             12456
GRID    69              22.615  18.0    0.0             12456
GRID    70              24.364  18.0    0.0             12456
GRID    71              26.112  18.0    0.0             12456
GRID    72              28.100  18.0    0.0             12456
GRID    73              29.609  18.0    0.0             12456
GRID    74              31.356  18.0    0.0             12456
GRID    75              33.105  18.0    0.0             12456
GRID    76              34.853  18.0    0.0             12456
GRID    77              36.601  18.0    0.0             12456
$                                                               $
GRID    78              22.306  21.0    0.0             12456
GRID    79              23.979  21.0    0.0             12456
GRID    80              25.653  21.0    0.0             12456
GRID    81              27.327  21.0    0.0             12456
GRID    82              29.000  21.0    0.0             12456
GRID    83              30.900  21.0    0.0             12456
GRID    84              32.347  21.0    0.0             12456
GRID    85              34.021  21.0    0.0             12456
GRID    86              35.694  21.0    0.0             12456
GRID    87              37.368  21.0    0.0             12456
GRID    88              39.041  .21.0   0.0             12456
$                                                               $
GRID    89              25.493  24.0    0.0             12456
GRID    90              27.092  24.0    0.0             12456
GRID    91              28.691  24.0    0.0             12456
GRID    92              30.290  24.0    0.0             12456
GRID    93              31.888  24.0    0.0             12456
GRID    94              33.700  24.0    0.0             12456
GRID    95              35.086  24.0    0.0             12456
GRID    96              36.685  24.0    0.0             12456
GRID    97              38.284  24.0    0.0             12456
GRID    98              39.883  24.0    0.0             12456
GRID    99              41.482  24.0    0.0             12456
$                                                               $
GRID    100             28.679  27.0    0.0             12456
GRID    101             30.204  27.0    0.0             12456
GRID    102             31.728  27.0    0.0             12456
GRID    103             33.252  27.0    0.0             12456
GRID    104             34.776  27.0    0.0             12456
GRID    105             36.700  27.0    0.0             12456
GRID    106             37.825  27.0    0.0             12456
GRID    107             39.349  27.0    0.0             12456
GRID    108             40.873  27.0    0.0             12456
GRID    109             42.398  27.0    0.0             12456
GRID    110             43.922  27.0    0.0             12456
$                                                               $
GRID    111             31.866  30.0    0.0             12456
GRID    112             33.316  30.0    0.0             12456
GRID    113             34.765  30.0    0.0             12456
GRID    114             36.215  30.0    0.0             12456
GRID    115             37.664  30.0    0.0             12456
GRID    116             39.500  30.0    0.0             12456
GRID    117             40.564  30.0    0.0             12456
GRID    118             42.013  30.0    0.0             12456
GRID    119             43.463  30.0    0.0             12456
GRID    120             44.912  30.0    0.0             12456
GRID    121             46.362  30.0    0.0             12456
$                                                               $
$               DIRECT INPUT MODE SHAPES                        $
$                                                               $
DMI     MODES   RDP     REC     121     5                       ABC
+BC     1       1       -.0405  -.0153  0.0     0.0     0.0     0.0     M1T6
+1T6    0.0     0.0     0.0     -0.0524 -0.104  0.00638 0.0352  0.0691  M1T14
```

```
+1T14   0.113   0.166   0.225   0.306   0.402   0.538   0.697   0.914   M1T22
+1T22   0.195   0.317   0.462   0.628   0.816   1.03    1.27    1.56    M1T30
+1T30   1.88    2.25    2.68    0.815   1.08    1.38    1.70    2.05    M1T38
+1T38   2.45    2.86    3.32    3.84    4.41    5.03    2.01    2.42    M1T46
+1T46   2.87    3.35    3.86    4.43    5.00    5.63    6.30    7.03    M1T54
+1T54   7.80    3.80    4.36    4.95    5.57    6.22    6.97    7.63    M1T62
+1T62   8.39    9.19    10.0    10.9    6.16    6.85    7.56    8.29    M1T70
+1T70   9.06    9.96    10.7    11.5    12.4    13.3    14.3    9.05    M1T78
+1T78   9.82    10.6    11.4    12.3    13.3    14.0    14.9    15.9    M1T86
+1T86   16.9    17.9    12.4    13.2    14.0    14.9    15.8    16.8    M1T94
+1T94   17.6    18.5    19.5    20.5    21.5    16.0    16.8    17.7    M1T102
+1T102  18.6    19.5    20.6    21.3    22.2    23.2    24.2    25.1    M1T110
+1T110  19.8    20.6    21.5    22.4    23.2    24.4    25.0    26.0    M1T118
+1T118  26.9    27.8    28.8    2       1       -0.351  -0.128  0.00    M2T3
+2T3    0.0     0.0     0.0     0.0     0.0     0.0     -0.686  -2.28   M2T11
+2T11   0.137   0.335   0.514   0.668   0.767   0.778   0.636   0.238   M2T19
+2T19   -0.719  -2.35   -4.79   1.62    2.16    2.59    2.83    2.83    M2T27
+2T27   2.50    1.74    0.444   -1.50   -4.11   -7.53   5.22    5.84    M2T35
+2T35   6.13    6.03    5.48    4.35    2.76    0.476   -2.47   -6.10   M2T43
+2T43   -10.6   10.5    10.7    10.4    9.51    8.05    5.90    3.28    M2T51
+2T51   -0.074  -4.09   -8.80   -14.4   16.5    15.8    14.4    12.5    M2T59
+2T59   9.91    6.41    2.86    -1.61   -6.72   -12.5   -19.2   22.0    M2T67
+2T67   20.0    17.4    14.3    10.5    5.47    1.16    -4.39   -10.5   M2T75
+2T75   -17.3   -24.9   25.9    22.6    18.70   14.3    9.40    3.17    M2T83
+2T83   -2.01   -8.48   -15.5   -23.0   -31.30  27.40   22.90   17.9    M2T91
+2T91   12.40   6.52    -0.653  -6.50   -13.60  -21.2   -29.2   -37.9   M2T99
+2T99   26.30   20.70   14.80   8.64    2.11    -6.59   -11.9   -19.4   M2T107
+2T107  -27.3   -35.6   -44.50  22.6    16.50   10.2    3.58    -3.28   M2T115
+2T115  -12.4   -17.8   -25.6   -33.7   -42.3   -52.6   3       1       M3T0
+3T0     0.083   0.028  0.0     0.0     0.0     0.0     0.0     0.0     M3T8
+3T8    0.0     -0.566  -2.30   0.004   -0.034  -0.092  -0.196  -0.371  M3T16
+3T16   -0.631  -1.12   -1.95   -3.60   -6.19   -10.3   -1.62   -0.366  M3T24
+3T24   -0.694  -1.20   -1.95   -3.06   -4.68   -6.99   -10.2   -14.30  M3T32
+3T32   -20.0   -1.714  -1.25   -2.02   -3.13   -4.64   -6.76   -9.32   M3T40
+3T40   -12.7   -16.80  -21.90  -28.4   -1.45   -2.36   -3.62   -5.29   M3T48
+3T48   -7.44   -10.20  -13.4   -17.2   -21.7   -26.90  -33.20  -1.70   M3T56
+3T56   -2.93   -4.55   -6.59   -9.06   -12.2   -15.3   -19.1   -23.3   M3T64
+3T64   -27.9   -33.4   -0.549  -1.96   -3.72   -5.83   -8.27   -11.4   M3T72
+3T72   -14.1   -17.4   -20.8   -24.5   -28.7   2.87    1.46    -0.219  M3T80
+3T80   -2.15   -4.31   -6.98   -9.13   -11.7   -14.3   -16.8   -19.6   M3T88
+3T88    9.08    7.77    6.27    4.61    2.83   0.748   -0.857  -2.67   M3T96
+3T96   -4.39   -5.96    -7.42   17.9    16.6    15.3    13.9    12.4   M3T104
+3T104  10.7    9.73    8.52    7.48    6.67    6.20    28.2    26.9    M3T112
+3T112  25.7    24.5    23.4    22.1    21.4    20.7    20.3    20.2    M3T120
+3T120  21.0    4       1       -1.08   -0.416  0.0     0.0     0.0     M4T5
+4T5    0.0     0.0     0.0     0.0     -1.42   -5.22   0.482   1.01    M4T13
+4T13   1.43    1.73    1.85    1.77    1.34    -0.436  -1.56   -4.92   M4T21
+4T21   -10.7   4.61    5.67    6.33    6.46    6.01    4.90    3.04    M4T29
+4T29   0.289   -3.49   -8.37   -15.5   12.80   13.2    12.9    11.7    M4T37
+4T37   9.63    6.71    3.29    -0.953  -5.84   -11.4   -18.8   21.7    M4T45
+4T45   20.1    17.6    14.4    10.5    5.98    1.43    -3.46   -8.44   M4T53
+4T53   -13.4   -19.6   26.5    22.3    17.6    12.6    7.55    2.16    M4T61
+4T61   -2.14   -6.40   -10.1   -13.0   -16.0   23.7    17.6    11.8    M4T69
+4T69   6.36    1.49    -3.13   -5.83   -7.94   -8.79   -8.18   -6.13   M4T77
+4T77   13.0    6.90    1.72    -2.42   -5.38   -7.16   -7.28   -5.93   M4T85
+4T85   -2.81   2.36    10.5    -2.49   -6.48   -9.10   -10.3   -9.97   M4T93
+4T93   -7.71   -4.51   0.890    8.34    18.2    32.5   -17.3   -17.6   M4T101
+4T101  -16.5   -14.10  -10.1   -2.75   2.83    12.1    23.7    38.2    M4T109
+4T109  58.3    -26.2   -22.9   -18.6   -13.0   -5.87   5.57    13.6    M4T117
+4T117  26.7    42.8    63.6    104.0   5       1       -0.053  -0.03   M5T2
+5T2    0.0     0.0     0.0     0.0     0.0     0.0     0.0     -2.72   M5T10
+5T10   -12.1   0.087   0.130   0.118   -0.006  -0.302  -0.821  -1.92   M5T18
+5T18   -4.00   -8.76   -17.0   -35.0   0.674   0.589   0.213   -0.596  M5T26
+5T26   -2.0    -4.24   -7.70   -12.9   -20.4   -30.7   -50.1   1.88    M5T34
+5T34   1.26    0.099   -1.75   -4.41   -8.14   -12.6   -18.2   -24.7   M5T42
+5T42   -32.1   -44.6   3.88    2.49    0.521   -2.04   -5.10   -8.63   M5T50
+5T50   -12.0   -15.2   -17.6   -18.7   -19.1   6.74    4.64    2.28    M5T58
+5T58   -0.164  -2.42   -4.27   -4.97   -4.35   -1.70   3.76    14.5    M5T66
+5T66   9.50    7.07    4.97    3.43     2.75   3.43    5.25    9.13    M5T74
+5T74   15.3    24.3    40.1    10.0     7.77   6.38    6.00    6.79    M5T82
+5T82   9.30    12.4    17.4    23.9     32.1   45.4    5.49    3.89    M5T90
+5T90   3.33    3.82    5.31    8.10     10.9   14.6    18.5    22.5    M5T98
+5T98   27.8    -5.57   -6.15   -5.98   -5.15   -3.85   -1.94   -0.901  M5T106
+5T106  0.032   -0.069  -1.91   -6.70   -21.1   -20.7   -20.2   -19.5   M5T114
+5T114  -18.9   -19.0   -19.7   -22.3   -27.4   -37.5   -70.9
$
EIGR    10      GIV     5.      200.            5                       +EI
+EI     MASS
$                                                                       $
$       DIRECT INPUT OF THE GENERALIZED MASS MATRIX FOR THE             $
$       NORMAL MODES ANALYSIS                                           $
$                                                                       $
DMI     MAA     RDP     DIAG    5       5                               +D3
+D3     1       1       1.      2       2       1.      3       3       +D4
+D4     1.      4       4       1.      5       5       1.
$                                                                       $
$       DIRECT INPUT OF THE GENERALIZED STIFFNESS MATRIX FOR THE        $
$       NORMAL MODES ANALYSIS                                           $
$                                                                       $
DMI     KAA     RDP     DIAG    5       5                               +D1
+D1     1       1       3637.72 2       2       57502.973       3       +D2
+D2     92282.714       4       330846.95       5       550752.7
$                                                                       $
$       DIRECT INPUT OF THE GENERALIZED STIFFNESS MATRIX FOR THE        $
$       FLUTTER ANALYSIS                                                $
$                                                                       $
DMI     KFLUT   CDP     DIAG    5       5                               +D5
```

```
+D5     1       1       3637.72 0.      2       2       57502.970.      +D6
+D6     3       3       92282.710.      4       4       330846.90.      +D7
+D7     5       5       550752.70.
$
$                                                                       $
$                                                                       $
$ * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * $
$                                                                       $
$                       Z A E R O    I N P U T                          $
$                                                                       $
$ * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * $
$                                                                       $
$ THIS CASE DEMONSTRATES THE USE OF THE TRANSONIC (ZTAIC) AND SUBSONIC  $
$ (ZONA6) METHODS FOR FLUTTER ANALYSIS OF THE AGARD STANDARD 445.6 WING $
$ (WEAKENED WING MODEL) WITH THE P-K AND K FLUTTER METHODS.             $
$                                                                       $
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
$                                                                       $
$                                                                       $
$                * AERO PARAMETERS / FLIGHT CONDITIONS *                $
$                                                                       $
$ AERO MODEL SYMMETRY IS REQUESTED ABOUT THE X-Z PLANE.  A REFERENCE    $
$ DENSITY OF 1.145E-07 SLINCHES (SEA LEVEL) AND REFERENCE CHORD OF     $
$ 21.96 INCHES IS SPECIFIED.                                            $
$                                                                       $
$       ACSID   XZSYM   RHOREF  REFC    REFB    REFS    GREF            $
AEROZ           YES     1.145-7 21.96
$                                                                       $
$                                                                       $
$ 6 MKAEROZ BULK DATA CARDS ARE SPECIFIED FOR AIC'S TO BE COMPUTED FOR  $
$ 3 MACH NUMBERS (0.678, 0.9 AND 0.95) AND FOR TWO METHODS.  THE FIRST  $
$ METHOD IS THE NONLINEAR (ZTAIC) AERODYNAMICS METHOD REQUESTED BY      $
$ SETTING THE METHOD FLAG = 1. THE SECOND METHOD IS FOR LINEAR (ZONA6)  $
$ AERODYNAMICS WITH THE METHOD FLAG SET TO 0. ALL AIC'S ARE SAVED IN    $
$ FILES FOR RESTART RUN CAPABILITY.  FILENAMES INCLUDE THE MACH NUMBER  $
$ AND METHOD NAME ACRONYM (ZT=ZTAIC AND Z6=ZONA6).  REDUCED FREQUENCY   $
$ INPUT ARE THE SAME FOR ALL MKAEROZ CARDS.                             $
$                                                                       $
$                       * * * MACH = 0.678 * * *                        $
$                                                                       $
$       IDMK    MACH    METHOD  IDFLT   SAVE    <--FILENAME-->  PRINT   $
MKAEROZ 10      0.678   1       0       SAVE    AGARD678ZT              +MK1
+MK1    0.001   .025    .05     0.075   0.09    0.09333 0.095   0.09666 +MK2
+MK2    0.10    .15     .2      .25     .3      .35     .4      .5
$                                                                       $
MKAEROZ 20      0.678   0       0       SAVE    AGARD678Z6              +MK1
+MK1    0.001   .025    .05     0.075   0.09    0.09333 0.095   0.09666 +MK2
+MK2    0.10    .15     .2      .25     .3      .35     .4      .5
$                                                                       $
$                       * * * MACH = 0.900 * * *                        $
$                                                                       $
MKAEROZ 30      0.90    1       0       SAVE    AGARD90ZT               +MK1
+MK1    0.001   .025    .05     0.075   0.09    0.09333 0.095   0.09666 +MK2
+MK2    0.10    .15     .2      .25     .3      .35     .4      .5
$                                                                       $
MKAEROZ 40      0.90    0       0       SAVE    AGARD90Z6               +MK1
+MK1    0.001   .025    .05     0.075   0.09    0.09333 0.095   0.09666 +MK2
+MK2    0.10    .15     .2      .25     .3      .35     .4      .5
$                                                                       $
$                       * * * MACH = 0.950 * * *                        $
$                                                                       $
MKAEROZ 50      0.95    1       0       SAVE    AGARD95ZT               +MK1
+MK1    0.001   .025    .05     0.075   0.09    0.09333 0.095   0.09666 +MK2
+MK2    0.10    .15     .2      .25     .3      .35     .4      .5
$                                                                       $
MKAEROZ 60      0.95    0       0       SAVE    AGARD95Z6               +MK1
+MK1    0.001   .025    .05     0.075   0.09    0.09333 0.095   0.09666 +MK2
+MK2    0.10    .15     .2      .25     .3      .35     .4      .5
$
$                                                                       $
$                                                                       $
$                       * WING MACROELEMENTS *                          $
$                                                                       $
$                                                                       $
$ AGARD STANDARD 445.6 WING (20 CHORDWISE AERO BOXES EVENLY CUT AND     $
$ 11 SPANWISE AERO BOXES WITH CUTS BASED ON SPAN LOCATIONS              $
$ SPECIFIED IN PERCENTAGE OF SPAN LENGTH IN AN AEFACT BULK DATA         $
$ CARD WITH SID OF 10). THE ZTAIC ENTRY REFERS TO A ZTAIC BULK DATA     $
$ CARD WITH AN ID OF 1001 THAT ESTABLISHES THE STEADY PRESSURE INPUT    $
$ FOR THIS WING MACROELEMENT.                                           $
$
$       WID     LABEL   ACOORD  NSPAN   NCHORD  LSPAN   ZTAIC   PAFOIL7 $
CAERO7  1001    WING            12      21      10      1001            +CA1
$       XRL     YRL     ZRL     RCH     LRCHD   ATTCHR                  $
+CA1    0.0     0.0     0.0     21.96   0       0                       +CA2
$       XRT     YRT     ZRT     TCH     LTCHD   ATTCHT                  $
+CA2    31.866  30.0    0.0     14.496  0       0
$                                                                       $
$       SID     D1      D2      ETC                                     $
AEFACT  10      0.0     16.45   27.25   37.75   47.75   57.15   65.75   +AE1
+AE1    73.5    80.     85.     90.     100.
$                                                                       $
$                                                                       $
$               * SURFACE SPLINE FIT ON THE WING *                      $
$                                                                       $
$                                                                       $
$ THE INFINITE PLATE SPLINE METHOD IS USED TO SPLINE THE WING AERO      $
```

```
$ BOXES TO THE WING STRUCTURE GRIDS.  THE SETK BULK DATA CARD REFERS     $
$ TO A PANLST1 BULK DATA CARD THAT SPLINES ALL OF THE WING AERO BOXES    $
$ TO THE GRID POINTS SPECIFIED IN THE SET1 (SID=60) BULK DATA CARD.      $
$                                                                        $
$       EID     MODEL   CP      SETK    SETG    DZ      EPS              $
SPLINE1 10      WING            10      60
$                                                                        $
$       SETID   MACROID BOX1    BOX2                                     $
PANLST1 10      1001    1001    1220
$                                                                        $
$       SID     G1      G2      ETC                                      $
SET1    60      1       THRU    121
$                                                                        $
$                                                                        $
$                                                                        $
$                     * * FLUTTER ANALYSIS * *                           $
$                                                                        $
$                                                                        $
$ SIX FLUTTER CARDS ARE USED.  EACH FLUTTER CARD REFERS TO A SPECIFIC    $
$ MKAEROZ BULK DATA CARD THAT SPECIFIES THE MACH NUMBER, REDUCED         $
$ FREQUENCIES AND METHOD USED (I.E.  LINEAR OR NONLINEAR) IN THE         $
$ ANALYSIS.  ALL FLUTTER CARDS REQUEST BOTH THE P-K AND K FLUTTER        $
$ SOLUTION METHODS AND REFERENCE THE SAME FLFACT CARD (SID=40) WHICH     $
$ LISTS THE VELOCITIES USED BY THE P-K METHOD.  EACH FLUTTER BULK DATA   $
$ CARD SPECIFIES DIFFERENT DENSITY RATIOS (VIA THE DENS ENTRY) TO        $
$ PERFORM A MATCHPOINT ANALYSIS.  AIR DENSITY VALUES ARE COMPUTED FROM:  $
$ DENSITY RATIO X RHOREF (WHERE RHOREF IS SPECIFIED BY THE AEROZ BULK    $
$ DATA CARD).                                                            $
$                                                                        $
$                 * MACH 0.678 - ZTAIC FLUTTER CASE *                    $
$                                                                        $
$        SETID  METHOD  DENS    IDMK    VEL     MLIST   KLIST   EFFID    $
FLUTTER 1       PKK     301     10      40                               +FL1
$        SYMXZ  SYMXY   EPS     CURVFIT PRINT                            $
+FL1    1
$                                                                        $
$       SID     F1      F2      ETC                                      $
FLFACT  40      8000.   8400.   9600.   10800.  12000.  13200.  14400.
FLFACT  301     .17     .18     .19     .20     .22
$                                                                        $
$                 * MACH 0.678 - ZONA6 FLUTTER CASE *                    $
$                                                                        $
FLUTTER 2       PKK     302     20      40                               +FL1
+FL1    1
FLFACT  302     .18     .182    .184    .186    .188
$                                                                        $
$                 * MACH 0.9   - ZTAIC FLUTTER CASE *                    $
$                                                                        $
FLUTTER 3       PKK     303     30      40                               +FL1
+FL1    1
FLFACT  303     .07     .075    .08     .0825   .085    .0875   .09
$                                                                        $
$                 * MACH 0.9   - ZONA6 FLUTTER CASE *                    $
$                                                                        $
FLUTTER 4       PKK     304     40      40                               +FL1
+FL1    1
FLFACT  304     .082    .084    .085    .086    .088
$                                                                        $
$                 * MACH 0.95  - ZTAIC FLUTTER CASE *                    $
$                                                                        $
FLUTTER 5       PKK     305     50      40                               +FL1
+FL1    1
FLFACT  305     .052    .054    .055    .056    .058    .059
$                                                                        $
$                 * MACH 0.95  - ZONA6 FLUTTER CASE *                    $
$                                                                        $
FLUTTER 6       PKK     306     60      40                               +FL1
+FL1    1
FLFACT  306     .065    .066    .067    .068    .069
$                                                                        $
$                                                                        $
$                                                                        $
$                                                                        $
$                * * TRANSONIC DATA FOR ZTAIC METHOD * *                 $
$                                                                        $
$                                                                        $
$ THE ZTAIC BULK DATA CARD IS REFERED TO BY THE ZTAIC ENTRY OF THE       $
$ CAERO7 (WING MACROELEMENT) BULK DATA CARD.  THE ZTAIC CARD REFERS      $
$ TO 3 MACHCP BULK DATA CARDS THAT ESTABLISH THE MACH NUMBER AND         $
$ STEADY INPUT PRESSURE RELATIONS.  SPAN LOCATION AND CORRESPONDING      $
$ STEADY PRESSURE FOR THAT SECTION ARE SPECIFIED BY THE SPANID AND       $
$ CHDCP ENTRIES, RESPECTIVELY. FOR EXAMPLE:                              $
$ THE STEADY PRESSURE INPUT FOR MACH 0.678 AT WING SPANWISE STATIONS 1   $
$ THRU 11 IS ESTABLISHED BY THE MACHCP CARD WITH ID=1001.  TO ESTABLISH  $
$ CORRESPONDENCE WITH AIC DATA, THIS STEADY PRESSURE MACH NUMBER OF      $
$ 0.678 MUST IDENTICALLY EXIST IN ONE OF THE MKAEROZ BULK DATA CARDS     $
$ WITH THE NONLINEAR METHOD ACTIVE (IN THIS CASE MKAEROZ WITH IDMK=10).  $
$ THE SPANWISE STATION INDICIES CORRESPOND TO THE WING MACROELEMENT      $
$ SPAN DIVISIONS CENTERLINE LOCATIONS.  IN THIS CASE AN AEFACT BULK      $
$ DATA CARD WITH SID=10 IS USED TO SPECIFY THE SPANWISE WING MACRO-      $
$ ELEMENT CUTS.  THEREFORE, SPANID=1 REFERS TO THE WING SPAN LOCATION    $
$ OF 8.225%, SPANID=2 REFERS TO THE WING SPAN LOCATION OF 21.85%, ETC.   $
$ THE CHORDWISE STRIP STEADY PRESSURE AT MACH 0.678 AT 8.225% IS GIVEN   $
$ IN A CHORDCP BULK DATA CARD WITH ID=1001, AT 21.85% IS GIVEN IN A      $
$ CHORDCP BULK DATA CARD WITH ID=1002, ETC.                              $
$                                                                        $
$ NOTE: THE CHORDCP BULK DATA CARDS ARE IN THE INCLUDE FILES (SEE BELOW) $
```

```
$                                                                           $
$       ID      NFLAP   MACHCP  MACHCP  ETC                                 $
ZTAIC   1001            1001    1002    1003
$                                                                           $
$       ID      MACH    IGRID   INDICA  SPANID  CHDCP   SPANID  CHDCP       $
MACHCP  1001    0.678   0       0       1       1001    2       2001        +MC1
$       SPANID  CHDCP   ETC                                                 $
+MC1    3       3001    4       4001    5       5001    6       6001        +MC2
+MC2    7       7001    8       8001    9       9001    10      10001       +MC3
+MC3    11      11001
$                                                                           $
MACHCP  1002    0.9     0       0       1       1002    2       2002        +MC1
+MC1    3       3002    4       4002    5       5002    6       6002        +MC2
+MC2    7       7002    8       8002    9       9002    10      10002       +MC3
+MC3    11      11002
$                                                                           $
MACHCP  1003    0.95    0       0       1       1003    2       2003        +MC1
+MC1    3       3003    4       4003    5       5003    6       6003        +MC2
+MC2    7       7003    8       8003    9       9003    10      10003       +MC3
+MC3    11      11003
$                                                                           $
$ TWO SETS OF STEADY PRESSURE INPUT DATA ARE USED IN THE PRESENT            $
$ ANALYSIS (TRANSONIC SMALL DISTURBANCE [FROM CAPTSD CODE] AND              $
$ NAVIER-STOKES [FROM ENSAERO CODE]). AN INCLUDE STATEMENT IS USED          $
$ TO REQUEST THE DESIRED PRESSURE TO BE USED.  ONLY ONE STEADY PRESSURE $
$ INPUT CAN BE USED AT A TIME.  THE USER IS INSTRUCTED TO UNCOMMENT THE $
$ DESIRED INCLUDE FILE CONTAINING THE DESIRED STEADY PRESSURE INPUT.        $
$ NOTE THAT STEADY PRESSURE INPUT FOR ALL 3 MACH NUMBERS                    $
$ (0.678,0.9,0.95) ARE INCLUDED IN EACH FILE.                               $
$                                                                           $
INCLUDE tsdcp.inp
$ INCLUDE nscp.inp
$                                                                           $
$                                                                           $
ENDDATA
```

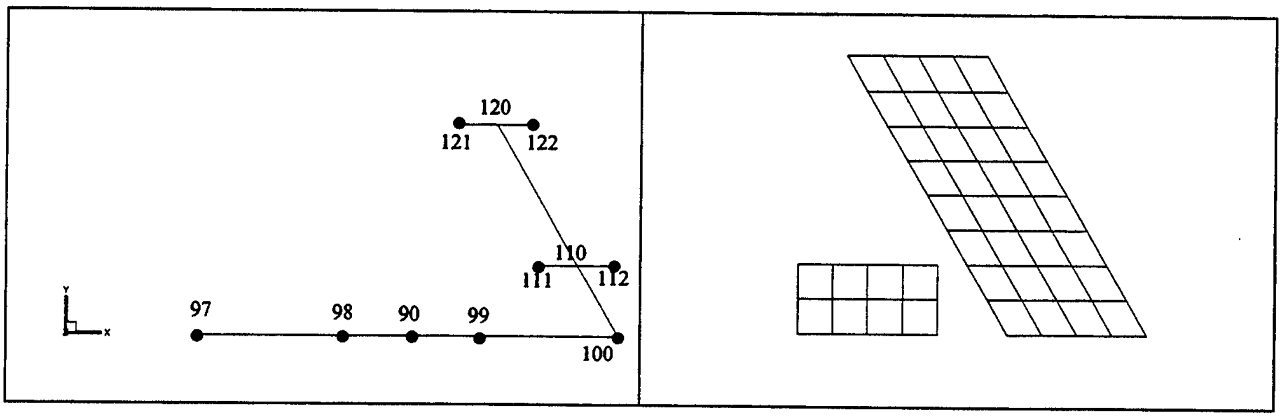
3.0 STATIC AEROELASTICITY (TRIM CASES)

3.1 Case 1: Forward Swept Wing in Level Flight (HA144A)

- ***Purpose:*** Demonstrate a wing + canard configuration symmetric trim case at subsonic (ZONA6 method) and supersonic (ZONA7 method) Mach numbers.

- ***Description of Input:***

A Forward Swept Wing (FSW) + canard airplane (modified HA144A case from the MSC/NASTRAN Aeroelastic Analysis User's Guide, Version 68) is considered for the present case. The structural and aerodynamic models are shown in Fig 3.1.1.



(a) **(b)**

Figure 3.1.1 Forward Swept Wing (FSW) (a) Structural Model and (b) Aerodynamic Model.

- Solution Control

Three symmetric static aeroelastic (SZAERO) analyses are requested for each of the desired flight Mach numbers and dynamic pressures. The boundary conditions are as follows: MPC=100 (Multipoint Contraints) of the rigid bar element connections of the wing structure; SPC=1 (Single Point Constraints) constraining all degrees of freedom of **GRID**'s 90, 97, 98, 99 and 100 except the z-axis translation and rotation about the y-axis; and SUPPORT=1 (Fictitious Support) for determinant reactions along the z-axis translation and rotation about the y-axis in the free body analysis.

- Structural Model

The reader is referred to the MSC/NASTRAN Aeroelastic Analysis User's Guide (Version 68) for a description of the structural model.

- Aerodynamic Parameters / Flight Conditions

An **AEROZ** bulk data card is used to specify a symmetric model about the x-z plane. A reference chord of 10ft, reference span of 40ft and reference area of 400ft^2 for the full model is specified. The reference grid about which the stability derivative calculations are made is defined by GREF=90.

Two **MKAEROZ** bulk data cards are used for Mach 0.9 and 1.3. Reduced frequency input is not required for this case, since only static aeroelastic analysis is performed.

- Aerodynamic Model

Two **CAERO7** bulk data cards are used to define the wing and canard wing macroelements with (chord aero boxes x span aero boxes) 4 x 8 and 4 x 2 evenly cut aerodynamic boxes, respectively. A **PAFOIL7** card is used to define the airfoil camber to simulate the incidence angle of 0.1 deg used in the corresponding MSC/NASTRAN case (HA144A). This was done to account for differences between test and theory experimental pressure data at some reference condition.

An **AESURFZ** card is used to define the entire canard as a control surface. A **COORD2R** card is used to define the y-axis hinge line of the control surface (in this case hinged at quarter chord).

- Spline

The inifinite plate spline method (**SPLINE1**) is used to spline all wing aerodynamic boxes to the structural grid points of the wing section. A beam spline (**SPLINE3**) is used to spline the canard to the structural grid points 98 and 99.

- Trim

Three **TRIM** bulk data cards are used to specify the following three trim flight conditions: (1) M=0.9, q=40 psf; (2) M=0.9, q=1200psf; and (3) M=1.3, q=1151psf; all in 1-G level flight. Trim parameters imposed for all three trim flight conditions are: no pitch rate (QRATE=0.0), 1-G load factor (NZ=32.2), and zero pitch acceleration (QACCEL=0.0). Aircraft angle-of-attack (ALPHA) and control surface rotation (ELEV) are set to FREE to be determined by the trim analysis.

- ***Description of Output:***

The three flight conditions considered in this case are: Mach 0.9 at dynamic pressures equal to 40psf and 1200psf as well as Mach 1.3 at a dynamic pressure of 1151psf. Table 3.1.1 shows the longitudinal aerodynamic stability derivatives of the rigid and flexible aircraft at Mach 0.9. Excellent agreement can be seen between the ASTROS* results and those of MSC/NASTRAN. Also, good agreement is obtained for the final trim results. Similarly, good agreement for the Mach 1.3 case can be seen in Table 3.1.2 for both stability derivatives and trim results.

Table 3.1.1 Longitudinal Stability Derivatives of FSW Aircraft at Mach 0.9.

	ASTROS* Results			MSC/NASTRAN Results		
Derivative	Value for Rigid Airplane	Unrestrained Value q=40 psf	Unrestrained Value q=1200 psf	Value for Rigid Airplane	Unrestrained Value q=40 psf	Unrestrained Value q=1200 psf
C_{Z_0}	0.0084	0.0085	0.0127	0.0084	0.0085	0.0127
C_{M_0}	-.0064	-0.0065	-0.0096	-0.006	-0.0061	-0.0087
C_{Z_α}	5.098	5.155	7.7412	5.071	5.127	7.772
$C_{M\alpha}$	-3.131	-3.173	-5.063	-2.871	-2.907	-4.557
C_{Z_q}	12.516	12.606	16.604	12.074	12.158	16.100
C_{M_q}	-10.875	-10.941	-13.874	-9.954	-10.007	-12.499
$C_{Z\delta e}$	0.2551	0.2597	0.4680	0.2461	0.2520	0.5219
$C_{M_{\delta e}}$	0.5671	0.5638	0.4143	0.5715	0.5678	0.3956

Note: Units are (1/rad).

Trim Results (flexible aircraft):

	ASTROS* Results		MSC/NASTRAN Results		
	q=40 psf	q=1200 psf	q=40 psf	q=1200 psf	
Pitch Rate	0.00	0.00	0.00	0.00	(User Input)
Load Factor	32.20	32.20	32.20	32.20	(User Input)
Pitch Acceleration	0.00	0.00	0.00	0.00	(User Input)
Angle of Attack	*9.54*	*0.177*	*9.69*	*0.079*	*(Computed)*
Control Surface Rotation	*31.48*	*1.156*	*28.22*	*1.107*	*(Computed)*

Note: Units in degrees.

Table 3.1.2 Longitudinal Stability Derivatives of FSW Aircraft at Mach 1.3.

	ASTROS* Results		MSC/NASTRAN Results	
Derivative	Value for Rigid Airplane	Unrestrained Value q=1151 psf	Value for Rigid Airplane	Unrestrained Value q=1151 psf
C_{Z_0}	0.0074	0.0087	0.0074	0.0086
C_{m_0}	-0.0072	-0.0085	-0.0072	-0.0083
C_{Z_α}	4.8473	5.8156	4.847	5.783
C_{m_α}	-3.8845	-4.800	-3.885	-4.728
C_{Z_q}	9.5399	9.9148	9.055	9.305
C_{m_q}	-10.5375	-10.8857	-10.149	-10.360
$C_{Z_{\delta_e}}$	0.6346	0.8467	0.6346	0.8802
$C_{m_{\delta_e}}$	0.2378	0.0348	0.2378	0.0105

Note: Units are (1/rad).

Trim Results (flexible aircraft):

	ASTROS* Result	NASTRAN	
Pitch Rate	0.00	0.00	(User Input)
Load Factor	32.20	32.20	(User Input)
Pitch Acceleration	0.00	0.00	(User Input)
Angle of Attack	*0.1025*	*-0.003*	*(Computed)*
Control Surface Rotation	*1.649*	*1.734*	*(Computed)*

Note: Units in degrees.

• *Input Data Listing:*

Listing 2.6 Input Data for the Forward Swept Wing in Level Flight (HA144A).

```
ASSIGN DATABASE HA144A PASS NEW DELETE
SOLUTION
TITLE = ZAERO TRIM CASE (HA144A): FORWARD SWEPT WING IN LEVEL FLIGHT
SUBTITLE = SUBSONIC (M=0.9) AND SUPERSONIC (M=1.2) STABILITY DERIVATIVES
ANALYZE
      BOUNDARY MPC = 100, SPC = 1, SUPPORT = 90
          LABEL = SYMMETRIC FLIGHT CONDITIONS, ZAERO MODULE AERODYNAMICS
          SAERO SYMMETRIC ( TRIM = 1 )
          PRINT TRIM
          LABEL = TRIM CASE #1 - M = 0.9, Q = 40 PSF
          SAERO SYMMETRIC ( TRIM = 2 )
          PRINT TRIM
          LABEL = TRIM CASE #2 - M = 0.9, Q = 1200 PSF
          SAERO SYMMETRIC ( TRIM = 3 )
          PRINT TRIM
          LABEL = TRIM CASE #3 - M = 1.3, Q = 1151 PSF
END
BEGIN BULK
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
GRID    90              15.     0.      0.
GRID    97              0.      0.      0.
GRID    98              10.     0.      0.
GRID    99              20.     0.      0.
GRID    100             30.     0.      0.
ASET    999     3       90
$                                                                       $
$                           * WING GRIDS *                              $
$                                                                       $
$       ID      CP      X1      X2      X3      CD      PS      SEID    $
GRID    111             24.61325 +5.    0.
GRID    110             27.11325 +5.    0.
GRID    112             29.61325 +5.    0.
GRID    121             18.83975+15.    0.
GRID    120             21.33975+15.    0.
GRID    122             23.83975+15.    0.
$                                                                       $
$                 * * STRUCTURAL STIFFNESS PROPERTIES * *               $
$                                                                       $
$                         * FUSELAGE STRUCTURE *                        $
$                                                                       $
$       EID     PID     GA      GB      X1,GO   X2      X3              $
CBAR    101     100     97      98      0.      0.      1.
CBAR    102     100     98      90      0.      0.      1.
CBAR    100     100     90      99      0.      0.      1.
CBAR    103     100     99      100     0.      0.      1.
$                                                                       $
$                                                                       $
$       PID     MID     A       I1      I2      J       NSM             $
PBAR    100     1       2.0     .173611 0.15    0.5                     +PB1
$       C1      C2      D1      D2      E1      E2      F1      F2      $
+PB1    1.0     1.0     1.0     -1.0    -1.0    1.0     -1.0    -1.0    +PB2
$       K1      K2      I12                                             $
+PB2                    0.0
$                                                                       $
$                           * WING STRUCTURE *                          $
$                                                                       $
$       EID     PID     GA      GB      X1,GO   X2      X3              $
CBAR    110     101     100     110     0.      0.      1.
CBAR    120     101     110     120     0.      0.      1.
$                                                                       $
$                                                                       $
$       SETID   EID     GA      GB      CNA     CNB     CMA     CMB     $
RBAR    100     111     110     111     123456
RBAR    100     112     110     112     123456
RBAR    100     121     120     121     123456
RBAR    100     122     120     122     123456
$                                                                       $
$       PID     MID     A       I1      I2      J       NSM             $
```

```
PBAR    101     1       1.5     0.173611+2.0    0.462963                +PB3
$       C1      C2      D1      D2      E1      E2      F1      F2      $
+PB3    0.5     3.0     0.5     -3.0    -0.5    3.0     -0.5    -3.0    +PB4
$       K1      K2      I12                                             $
+PB4                    0.0
$                                                                       $
$       MID     E       G       NU      RHO     A       TREF    GE      $
MAT1    1       1.44+9  5.40+8
$                                                                       $
$                      * * MASS AND INERTIA PROPERTIES * *              $
$                                                                       $
$                            * FUSELAGE MASSES *                        $
$                                                                       $
$       EID     G       CID     M       X1      X2      X3              $
CONM2   97      97      0       46.6215
CONM2   98      98      0       46.6215
CONM2   99      99      0       46.6215
CONM2   100     100     0       46.6215
$                                                                       $
$                              * WING MASSES *                          $
$                                                                       $
CONM2   111     111     0       18.648
CONM2   112     112     0       12.4324
CONM2   121     121     0       18.648
CONM2   122     122     0       12.4324
$                                                                       $
$                                                                       $
$                        * * STRUCTURAL CONSTRAINTS * *                 $
$                                                                       $
$       SID     C       G1      G2      G3      G4                      $
SPC1    1       1246    90
SPC1    1       246     97      98      99      100
$                                                                       $
$       SETID   ID      C                                               $
SUPORT  90      90      35
$                                                                       $
$ * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * $
$                                                                       $
$                           Z A E R O   I N P U T                       $
$                                                                       $
$ * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * $
$                                                                       $
$ THIS CASE DEMONSTRATES A FORWARD SWEPT WING + CANARD CONFIGURATION    $
$ UNDER STEADY AERO TRIM CASES AT SUBSONIC AND SUPERSONIC MACH NUMBERS  $
$                                                                       $
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
$                                                                       $
$                                                                       $
$                 * AERO PARAMETERS / FLIGHT CONDITIONS *               $
$                                                                       $
$ THE REFERENCE GRID FOR STABILITY DERIVATIVE CALCULATIONS IS DEFINED   $
$ BY GREF=90 WHICH IS LOCATED AT X=15, Y=0.0 AND Z=0.0. THE REFERENCE   $
$ CHORD IS CHOSEN AS 10FT, REFERENCE SPAN IS CHOSEN AS 40FT AND THE     $
$ REFERENCE AREA IS 400 SQ FT FOR THE FULL MODEL.                       $
$                                                                       $
$       ACSID   XZSYM   RHOREF  REFC    REFB    REFS    GREF            $
AEROZ   0       YES     1.0     10.0    40.0    400.0   90
$                                                                       $
$ MKAEROZ BULK DATA CARDS MUST EXIST FOR STEADY AERODYNAMICS AS WELL    $
$ AS UNSTEADY AERODYNAMICS.  IN THIS CASE TWO MACH NUMBERS ARE          $
$ COMPUTED FOR M=0.9 AND M=3.0.  NO REDUCED FREQUENCIES ARE INPUT       $
$ BECAUSE A TRIM RATHER THAN FLUTTER ANALYSIS IS DESIRED.               $
$ NOTE: BOTH TRIM AND FLUTTER DISCIPLINES MAY REFERENCE ONE MKAEROZ     $
$ BULK DATA CARD.                                                       $
$                                                                       $
$       IDMK    MACH    METHOD  IDFLT   SAVE    <--FILENAME--> PRINT    $
MKAEROZ 1000    0.9
MKAEROZ 2000    1.3
$                                                                       $
$                                                                       $
$                          * WING MACROELEMENTS *                       $
$                                                                       $
$                                                                       $
$ FORWARD SWEPT WING - 4 x 8 AERO BOXES EVENLY CUT                      $
$       WID     LABEL   ACOORD  NSPAN   NCHORD  LSPAN   ZTAIC   PAFOIL7 $
CAERO7  1100    WING            9       5       0               1101    +CA1
$       XRL     YRL     ZRL     RCH     LRCHD   ATTCHR                  $
+CA1    25.     0.      0.      10.     0       0                       +CA2
$       XRT     YRT     ZRT     TCH     LTCHD   ATTCHT                  $
+CA2    13.4529920.     0.      10.     0       0
$                                                                       $
$ A PAFOIL7 CARD IS USED TO DEFINE THE AIRFOIL CROSS-SECTION FOR THE    $
$ ZONA7U METHOD.  LIKE THE DMI INPUT USED IN THE  HA144A OF THE         $
$ MSC/NASTRAN AEROELASTIC USER GUIDE, THE PAFOIL7 WILL ACCOUNT FOR THE  $
$ DIFFERENCES BETWEEN TEST AND THEORY (WING CAMBER EFFECTS).            $
$                                                                       $
$       ID      ITAX    ITHR    ICAMR   RADR    ITHT    ICAMT   RADT    $
PAFOIL7 1101    1102    1103    1104    0.0     1103    1104    0.0
AEFACT  1102    0.0     50.0    100.0
AEFACT  1103    0.0     0.0     0.0
$ AEFACT TO DESCRIBE THE AIRFOIL CAMBER (0.1 DEG INCIDENCE)             $
AEFACT  1104    0.0     -0.0872 -0.1744
$                                                                       $
$ CANARD - 4 x 2 AERO BOXES EVENLY CUT                                  $
CAERO7  1000    CANARD          3       5       0                       +CA1
+CA1    10.     0.0     0.0     10.     0       0                       +CA2
+CA2    10.     5.0     0.0     10.     0       0
```

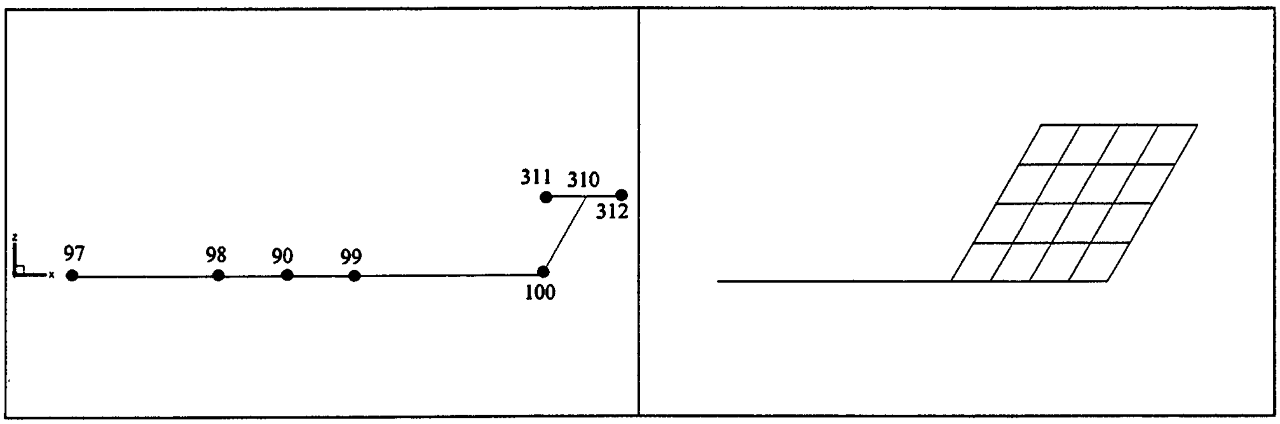
```
$                                                                       $
$ THE ENTIRE CANARD IS DEFINED AS A CONTROL SURFACE BY AN AESURFZ BULK  $
$ DATA CARD.  THE AESURFZ CARD REFERS TO A PANLST2 BULK DATA CARD WHICH $
$ SPECIFIES THAT AERO BOXES 1000 THROUGH 1007 BE USED AS THE CONTROL    $
$ SURFACE.  THE AESURFZ CARD REFERENCES A RECTANGULAR COORDINATE SYSTEM $
$ (COORD2R) THAT DEFINES THE Y-AXIS OF THE CONTROL SURFACE HINGE LINE.  $
$ THE CONTROL SURFACE IS HINGED ABOUT ITS QUARTER-CHORD.                $
$                                                                       $
$       LABEL   TYPE    CID     SETK    SETG
AESURFZ ELEV    SYM     1       1000
$                                                                       $
$       SETID   MACROID BOX1    BOX2    ETC                             $
PANLST2 1000    1000    1000    1001    1002    1003    1004    1005    +P1
+P1     1006    1007
$                                                                       $
$       CID     RID     A1      A2      A3      B1      B2      B3      $
CORD2R  1       0       12.5    0.0     0.0     12.5    0.0     10.0    +CRD2
$       C1      C2      C3                                              $
+CRD2   20.0    0.0     10.0
$                                                                       $
$                                                                       $
$                    * SURFACE SPLINE FIT ON THE WING *                 $
$                                                                       $
$                                                                       $
$ THE INFINITE PLATE SPLINE METHOD IS USED TO SPLINE THE WING AERO      $
$ BOXES TO THE WING STRUCTURE GRIDS.  THE SETK BULK DATA CARD REFERS    $
$ TO A PANLST1 BULK DATA CARD THAT SPLINES ALL OF THE WING AERO  BOXES  $
$ TO THE GRID POINTS SPECIFIED IN THE SET1 (SID=1105) BULK DATA CARD.   $
$                                                                       $
$       EID     MODEL   CP      SETK    SETG    DZ      EPS             $
SPLINE1 1601    WING            1100    1105    0.0
$                                                                       $
$       SETID   MACROID BOX1    BOX2                                    $
PANLST1 1100    1100    1100    1131
$                                                                       $
$       SID     G1      G2      ETC                                     $
SET1    1105    100     110     111     112     120     121     122
$                                                                       $
$                                                                       $
$ THE BEAM SPLINE METHOD IS USED ON THE CANARD.  THE SETK ENTRY REFERS  $
$ TO THE PANLST2 BULK DATA CARD PREVIOUSLY DEFINED FOR THE AESURFZ BULK $
$ DATA CARD LISTING ALL AERO BOXES LOCATED ON THE CANARD.               $
$                                                                       $
$       EID     MODEL   SETK    SETG    DZ      DTOR    CID     DTHX    $
SPLINE2 1501    CANARD  1000    1000    0.0     1.0     1       -1.0    +SP1
$       DTHY                                                            $
+SP1    -1.0
$                                                                       $
$       SID     G1      G2      ETC                                     $
SET1    1000    98      99
$                                                                       $
$                                                                       $
$                           * TRIM CONDITIONS *                         $
$                                                                       $
$                                                                       $
$ THREE TRIM CONDITIONS (ALL AT 1G LEVEL FLIGHT) ARE CONSIDERED FOR     $
$ THIS CASE. 1) M=0.9, Q=40.0 PSF, 2) M=0.9, Q=1200.0 PSF AND           $
$ 3) M=1.3, Q=1151 PSF.  IDMK ENTRIES REFER TO MKAEROZ CARDS THAT       $
$ SPECIFY THE MACH NUMBER FOR EACH TRIM CASE.  DYNAMIC PRESSURES OF     $
$ 40.0, 1200.0, AND 1151.0 ARE SPECIFIED IN THE QDP ENTRIES.  A TRIM    $
$ TYPE OF PITCH IS SPECIFIED FOR SYMMETRIC TRIM OF LIFT AND PITCHING    $
$ MOMENT (2 DOF).  TRIM FLIGHT CONDITIONS IMPOSED ARE NO PITCH RATE     $
$ (QRATE=0.0) ONE G LOAD FACTOR (NZ=32.2) AND ZERO PITCH ACCELERATION   $
$ (QACCEL=0.0).  THE ANGLE-OF-ATTACK (ALPHA) AND CANARD SURFACE         $
$ ROTATION (ELEV) ARE SET TO FREE TO BE DETERMINED BY THE TRIM ANALYSIS.$
$                                                                       $
$ TRIM CONDITION 1: 1 G LEVEL FLIGHT AT LOW SPEED                       $
$                                                                       $
$       TRIMID  IDMK    QDP     TRMTYP  EFFID   VO      PRINT           $
TRIM    1       1000    40.0    PITCH           1.0     -2              +TR1
$       LABEL1  VAL1    LABEL2  VAL2    ETC                             $
+TR1    QRATE   0.0     NZ      32.2    QACCEL  0.0     ALPHA   FREE    +TR2
+TR2    ELEV    FREE
$                                                                       $
$ TRIM CONDITION 2: 1 G LEVEL FLIGHT AT HIGH SUBSONIC SPEED             $
$                                                                       $
TRIM    2       1000    1200.0  PITCH           1.0     -2              +TR3
+TR3    QRATE   0.0     NZ      32.2    QACCEL  0.0     ALPHA   FREE    +TR4
+TR4    ELEV    FREE
$                                                                       $
$ TRIM CONDITION 3: 1 G LEVEL FLIGHT AT LOW SUPERSONIC SPEED            $
$                                                                       $
TRIM    3       2000    1151.0  PITCH           1.0     -2              +TR5
+TR5    QRATE   0.0     NZ      32.2    QACCEL  0.0     ALPHA   FREE    +TR6
+TR6    ELEV    FREE
$                                                                       $
$                                                                       $
ENDDATA
```

3.2 Case 2: Forward Swept Wing Airplane in Antisymmetric Maneuvers (HA144D)

- ***Purpose:*** Demonstrate a wing + canard + vertical tail fin configuration antisymmetric trim case at subsonic (ZONA6 method) Mach number.

- ***Description of Input:***

The FSW Airplane of Case 1 (Section 3.1) is reconsidered here for its lateral-directional stability characteristics. The half-span model is modified to add a sweptback vertical tail fin and to consider the antisymmetrical motions of the aircraft. The structural and aerodynamic models of the vertical tail fin portion of the aircraft is shown in Fig 3.2.1. The wing + canard aerodynamic models remain unchanged from those of Case 1 (Section 3.1) and are shown in Fig 3.1.1.



(a) (b)

Figure 3.2.1 Side View of FSW Showing the Vertical Tail Fin (a) Structural Model and (b) Aerodynamic Model.

- Solution Control

Two symmetric static aeroelastic (SZAERO) analyses are requested both at Mach 0.9 and q=1200psf. The boundary conditions are as follows: MPC=100 (Multipoint Constraints) of the rigid bar element connections of the aircraft structure; SPC=2 (Single Point Constraints) constraining all degrees of freedom of **GRID**'s 90, 97, 98, 99 and 100 except the y-axis translation (lateral motion), rotation about the x-axis (roll), and rotation about the z-axis (yaw); and SUPPORT=20 (Fictitious Support) for determinant reactions along the y-axis translation, rotations about the x- and z-axes in the free body analysis.

- Structural Model

The reader is referred to the MSC/NASTRAN Aeroelastic Analysis User's Guide (Version 68) for a description of the structural model.

- Aerodynamic Parameters / Flight Conditions

The flight conditions for this case are the same as those of Case 1 (Section 3.1), except only one **MKAEROZ** bulk data card is used for Mach 0.9

- Aerodynamic Model

The aerodynamic model is the same as that of Case 1 (Section 3.1) except for the control surface definitions. Two control surfaces are defined for the present case. An aileron is defined on the wing (aerodynamic boxes 1119, 1123, 1127 and 1131) and a rudder is defined on the vertical tail fin (aerodynamic boxes 3103, 3107, 3111, 3115). **COORD2R** cards are used to define the y-axis hinge line of the control surfaces.

- Spline

The spline of the aerodynamic model to the structure is the same as that of Case 1 except for the additional splining of the vertical tail fin to the tail structure. All 16 aerodynamic boxes of the vertical tail fin (3100 through 3115) are splined by the infinite plate spline method to the tail structural **GRID**'s (100, 311, 310, 312).

- Trim

Two subsonic trim cases are considered. The first, **TRIM** 1, finds the steady roll solution for an aileron rotation of 25 degrees (AILERON), zero yaw acceleration (RACCEL), zero roll acceleration (PACCEL), zero yaw rate (RRATE) and no side slip acceleration (NY). Computed trim parameters are the yaw angle (BETA), rudder deflection angle (RUDDER) and roll rate (PRATE). The second trim condition, **TRIM** 2, is an abrupt roll solution with the same trim conditions imposed in the first trim case, except that roll rate (PRATE) is set to zero and the roll acceleration (PACCEL) is set to FREE to be computed by the trim analysis.

- ***Description of Output:***

Two trim cases (one for steady roll and one for abrupt roll) are examined at Mach 0.9 and dynamic pressure 1200psf. The results of the lateral-directional stability characteristics of ASTROS* and MSC/NASTRAN are compared in Table 3.2.1. Excellent agreement is seen between the two sets of results.

The trim results of the first trim case is shown in Table 3.2.2 and the second in Table 3.2.3. Good agreement are obtained for both trim cases.

Table 3.2.1 Lateral Aerodynamic Stability Derivatives of FSW Aircraft with Vertical Tail at Mach 0.9.

	ASTROS* Results		MSC/NASTRAN Results	
Derivative	Value for Rigid Airplane	Unrestrained Value q=1200 psf	Value for Rigid Airplane	Unrestrained Value q=1200 psf
C_{Y_β}	-0.7241	-0.7375	-0.7158	-0.7260
C_{l_β}	0.0340	0.0276	0.0328	0.0271
C_{n_β}	-0.2704	-0.2754	-0.2592	-0.2630
C_{Y_p}	-0.0824	-0.1015	-0.07965	-0.09466
C_{l_p}	-0.4207	-0.4364	-0.4185	-0.4448
C_{n_p}	-0.0278	-0.0348	-0.0261	-0.0314
C_{Y_r}	-0.7461	-0.7528	-0.7233	-0.7285
C_{l_r}	0.0453	0.0382	0.0429	0.0363
C_{n_r}	-0.2950	-0.2974	-0.2775	-0.2794
$C_{Y_{\delta r}}$	0.3785	0.3641	0.3491	0.3381
$C_{l_{\delta r}}$	-0.0414	-0.0361	-0.03745	-0.03229
$C_{n_{\delta r}}$	0.1902	0.1848	0.1707	0.1665
$C_{Y_{\delta a}}$	-0.1214	-0.1088	-0.1082	-0.1026
$C_{l_{\delta a}}$	-0.2993	-0.2840	-0.2748	-0.2625
$C_{n_{\delta a}}$	-0.0458	-0.0411	-0.03948	-0.03753

Note: Units are (1/rad).

Table 3.2.2 Trim Set 1 - Steady Roll Solution at Mach 0.9 (flexible aircraft).

	ASTROS* Results	MSC/NASTRAN Results	
	q=1200 psf	q=1200 psf	
Control Surface Rotation (Deg)	25.00	25.00	(User Input)
Yaw Angle (Deg)	*-0.79*	*-1.05*	*(Computed)*
Yaw Acceleration (Rad/s/s)	0.00	0.00	(User Input)
Roll Acceleration (Rad/s/s)	0.00	0.00	(User Input)
Yaw Rate (Deg/s)	0.00	0.00	(User Input)
Control Surface Rotation (Deg)	*1.29*	*1.18*	*(Computed)*

Roll Rate (Deg/s)	*-0.821*	*-0.745*	*(Computed)*
Side-Slip Acceleration (Rad/s/s)	0.00	0.00	(User Input)

Table 3.2.3 Trim Set 2 - Abrupt Roll Solution at Mach 0.9 (flexible aircraft).

	ASTROS* Results	MSC/NASTRAN Results	
	q=1200 psf	q=1200 psf	
Control Surface Rotation (Deg)	25.00	25.00	(User Input)
Yaw Angle (Deg)	*-3.78*	*-3.61*	*(Computed)*
Yaw Acceleration (Rad/s/s)	0.00	0.00	(User Input)
Roll Acceleration (Rad/s/s)	*-155*	*-143*	*(Computed)*
Yaw Rate (Deg/s)	0.00	0.00	(User Input)
Control Surface Rotation (Deg)	*0.61*	*0.63*	*(Computed)*
Roll Rate (Deg/s)	0.00	0.00	(User Input)
Side-Slip Acceleration (Rad/s/s)	0.00	0.00	(User Input)

- ***Input Data Listing:***

Listing 2.7 Input Data for the Forward Swept Wing in Level Flight (HA144D).

```
ASSIGN DATABASE HA144D PASS NEW DELETE
SOLUTION
TITLE = ZAERO TRIM CASE (HA144D): FORWARD SWEPT WING WITH VERTICAL TAIL
SUBTITLE = SUBSONIC (M=0.9) LATERAL STABILITY DERIVATIVES
ANALYZE
      BOUNDARY MPC=100,SPC=2,SUPPORT=20
          LABEL = ANTISYMMETRIC FLIGHT CONDITIONS, ZAERO MODULE AERODYNAMICS
          SAERO ANTISYMMETRIC ( TRIM=1 )
          PRINT TRIM
          SAERO ANTISYMMETRIC ( TRIM=2 )
          PRINT TRIM
END
BEGIN BULK
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
GRID    90              15.     0.      0.
GRID    97              0.      0.      0.
GRID    98              10.     0.      0.
GRID    99              20.     0.      0.
GRID    100             30.     0.      0.
$                                                                       $
$                           * WING GRID *                               $
$                                                                       $
$       ID      CP      X1      X2      X3      CD      PS      SEID
GRID    111             24.61325 +5.    0.
GRID    110             27.11325 +5.    0.
GRID    112             29.61325 +5.    0.
GRID    121             18.83975+15.    0.
GRID    120             21.33975+15.    0.
GRID    122             23.83975+15.    0.
$                                                                       $
$                           * VERTICAL FIN *
GRID    310             32.8667         5.
GRID    311             30.3867         5.
GRID    312             35.3867         5.
$
CBAR    310     301     100     310     0.      0.      1.
$
PBAR    301     1       .75     .086806 1.      .23148                  +PB2
+PB2    .5      3.      .5      -3.     -.5     3.      -.5     -3.     +PB3
+PB3                    0.
$                                                                       $
RBAR    100     311     310     311     123456
RBAR    100     312     310     312     123456
```

```
$                                                                      $
CONM2   311     311     0       0.93167
CONM2   312     312     0       0.62112
$                                                                      $
$           * * STRUCTURAL STIFFNESS PROPERTIES * *                    $
$                                                                      $
$                    * FUSELAGE STRUCTURE *                            $
$                                                                      $
$       EID     PID     GA      GB      X1,GO   X2      X3
CBAR    101     100     97      98      0.      0.      1.
CBAR    102     100     98      90      0.      0.      1.
CBAR    100     100     90      99      0.      0.      1.
CBAR    103     100     99      100     0.      0.      1.
$                                                                      $
$                                                                      $
$       PID     MID     A       I1      I2      J       NSM
PBAR    100     1       2.0     .173611 0.15    0.5                    +PB1
$       C1      C2      D1      D2      E1      E2      F1      F2
+PB1    1.0     1.0     1.0     -1.0    -1.0    1.0     -1.0    -1.0   +PB2
$       K1      K2      I12
+PB2                    0.0
$                                                                      $
$                      * WING STRUCTURE *                              $
$                                                                      $
$       EID     PID     GA      GB      X1,GO   X2      X3
CBAR    110     101     100     110     0.      0.      1.
CBAR    120     101     110     120     0.      0.      1.
$                                                                      $
$                                                                      $
$       SETID   EID     GA      GB      CNA     CNB     CMA     CMB
RBAR    100     111     110     111     123456
RBAR    100     112     110     112     123456
RBAR    100     121     120     121     123456
RBAR    100     122     120     122     123456
$                                                                      $
$       PID     MID     A       I1      I2      J       NSM
PBAR    101     1       1.5     0.173611+2.0    0.462963               +PB3
$       C1      C2      D1      D2      E1      E2      F1      F2
+PB3    0.5     3.0     0.5     -3.0    -0.5    3.0     -0.5    -3.0   +PB4
$       K1      K2      I12
+PB4                    0.0
$                                                                      $
$       MID     E       G       NU      RHO     A       TREF    GE
MAT1    1       1.44+9  5.40+8
$                                                                      $
$            * * MASS AND INERTIA PROPERTIES * *                       $
$                                                                      $
$                    * FUSELAGE MASSES *                               $
$                                                                      $
$       EID     G       CID     M       X1      X2      X3
CONM2   97      97      0       46.6215
CONM2   98      98      0       46.6215
CONM2   99      99      0       46.6215
CONM2   100     100     0       46.6215
$                                                                      $
$                      * WING MASSES *                                 $
$                                                                      $
CONM2   111     111     0       18.648
CONM2   112     112     0       12.4324
CONM2   121     121     0       18.648
CONM2   122     122     0       12.4324
$                                                                      $
$               * * STRUCTURAL CONSTRAINTS * *                         $
$                                                                      $
$       SID     C       G1      G2      G3      G4
SPC1    2       135     90
SPC1    2       35      97      98      99      100
$                                                                      $
$       SETID   ID      C
SUPORT  20      90      246
$                                                                      $
$                                                                      $
$ * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * $
$                                                                      $
$                         Z A E R O   I N P U T                        $
$                                                                      $
$ * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * $
$                                                                      $
$ THIS CASE DEMONSTRATES A FORWARD SWEPT WING + CANARD + VERTICAL TAIL $
$ CONFIGURATION UNDER STEADY AERO TRIM CASES AT SUBSONIC MACH NUMBER   $
$                                                                      $
$...1..|...2...|...3...|...4...|...5...|...6...|...7...|...8...|...9...|...10..|
$                                                                      $
$                                                                      $
$          * AERO PARAMETERS / FLIGHT CONDITIONS *                     $
$                                                                      $
$ THE REFERENCE GRID FOR STABILITY DERIVATIVE CALCULATIONS IS DEFINED  $
$ BY GREF=90 WHICH IS LOCATED AT X=15, Y=0.0 AND Z=0.0. THE REFERENCE  $
$ CHORD IS CHOSEN AS 10FT, REFERENCE SPAN IS CHOSEN AS 40FT AND THE    $
$ REFERENCE AREA IS 400 SQ FT FOR THE FULL MODEL.                      $
$                                                                      $
$       ACSID   XZSYM   RHOREF  REFC    REFB    REFS    GREF           $
AEROZ   0       YES     1.0     10.0    40.0    400.0   90
$                                                                      $
$       IDMK    MACH    METHOD  IDFLT   SAVE    <--FILENAME-->  PRINT  $
MKAEROZ 90      0.9     0       0
$                                                                      $
```

```
$                                                                         $
$                             * WING MACROELEMENTS *                      $
$                                                                         $
$                                                                         $
$ FORWARD SWEPT WING - 4 x 8 AERO BOXES EVENLY CUT                        $
$       WID     LABEL   ACOORD  NSPAN   NCHORD  LSPAN   ZTAIC   PAFOIL7 $
CAERO7  1100    WING            9       5       0               1101    +CA1
$       XRL     YRL     ZRL     RCH     LRCHD   ATTCHR                  $
+CA1    25.     0.      0.      10.     0       0                       +CA2
$       XRT     YRT     ZRT     TCH     LTCHD   ATTCHT                  $
+CA2    13.4529920.     0.      10.     0       0
$                                                                         $
$ A PAFOIL7 CARD IS USED TO DEFINE THE AIRFOIL CROSS-SECTION FOR THE      $
$ ZONA7U METHOD.  LIKE THE DMI INPUT USED IN THE  HA144A OF THE           $
$ MSC/NASTRAN AEROELASTIC USER GUIDE, THE PAFOIL7 WILL ACCOUNT FOR THE    $
$ DIFFERENCES BETWEEN TEST AND THEORY (WING CAMBER EFFECTS).              $
$                                                                         $
$       ID      ITAX    ITHR    ICAMR   RADR    ITHT    ICAMT   RADT      $
PAFOIL7 1101    1102    1103    1104    0.0     1103    1104    0.0
AEFACT  1102    0.0     50.0    100.0
AEFACT  1103    0.0     0.0     0.0
$ AEFACT TO DESCRIBE THE AIRFOIL CAMBER (0.1 DEG INCIDENCE)               $
AEFACT  1104    0.0     -0.0872 -0.1744
$                                                                         $
$ CANARD - 4 x 2 AERO BOXES EVENLY CUT                                    $
CAERO7  1000    CANARD          3       5       0                       +CA1
+CA1    10.     0.0     0.0     10.     0       0                       +CA2
+CA2    10.     5.0     0.0     10.     0       0
$                                                                         $
$ DEFINITION OF VERTICAL FIN 4 x 4 EVENLY CUT                             $
CAERO7  3100    FIN             5       5       0                       +CA1
+CA1    30.7735 0.      10.     10.     0       0                       +CA2
+CA2    25.     0.      0.      10.     0       0
$                                                                         $
$                                                                         $
$ TWO CONTROL SURFACES ARE DEFINED: AN AILERON ON THE MAIN WING  ( AERO $
$ BOXES 1119, 1123, 1127 AND 1131 ) AND A RUDDER ON THE VERTICAL TAIL   $
$ ( AERO BOXES 3103, 3107, 3111 AND 3115). Y-AXES OF THE CONTROL SURFACE$
$ HINGE LINES ARE SPECIFIED VIA THE CORD2R BULK DATA CARDS.               $
$                                                                         $
$       LABEL   TYPE    CID     SETK    SETG
AESURFZ AILERON ANTISYM 110     2000
$       SETID   MACROID BOX1    BOX2    ETC                               $
PANLST2 2000    1100    1119    1123    1127    1131
$                                                                         $
AESURFZ RUDDER  ANTISYM 301     3000
$                                                                         $
PANLST2 3000    3100    3103    3107    3111    3115
$                                                                         $
$       CID     RID     A1      A2      A3      B1      B2      B3        $
CORD2R  110     0       26.7265 10.     0.      26.7265 10.     -10.    +CORD1
$       C1      C2      C3                                                $
+CORD1  36.7265 15.7735 0.
$                                                                         $
CORD2R  301     0       32.5    0.      0.      32.5    -10.    0.      +CORD1
+CORD1  22.5    0.      5.7735
$                                                                         $
$                                                                         $
$                      * SURFACE SPLINE FIT ON THE WING *                 $
$                                                                         $
$                                                                         $
$ THE INFINITE PLATE SPLINE METHOD IS USED TO SPLINE THE WING AERO        $
$ BOXES TO THE WING STRUCTURE GRIDS.  THE SETK BULK DATA CARD REFERS      $
$ TO A PANLST1 BULK DATA CARD THAT SPLINES ALL OF THE WING AERO  BOXES    $
$ TO THE GRID POINTS SPECIFIED IN THE SET1 (SID=1105) BULK DATA CARD.     $
$                                                                         $
$       EID     MODEL   CP      SETK    SETG    DZ      EPS               $
SPLINE1 1601    WING            1100    1105    0.0
$                                                                         $
$       SETID   MACROID BOX1    BOX2                                      $
PANLST1 1100    1100    1100    1131
$                                                                         $
$       SID     G1      G2      ETC                                       $
SET1    1105    100     110     111     112     120     121     122
$                                                                         $
$                                                                         $
$ THE BEAM SPLINE METHOD IS USED ON THE CANARD.  THE SETK ENTRY REFERS    $
$ TO THE PANLST2 BULK DATA CARD PREVIOUSLY DEFINED FOR THE AESURFZ BULK $
$ DATA CARD LISTING ALL AERO BOXES LOCATED ON THE CANARD.                 $
$                                                                         $
$       EID     MODEL   SETK    SETG    DZ      DTOR    CID     DTHX      $
SPLINE2 1501    CANARD  1000    1000    0.0     1.0     1       -1.0    +SP1
$       DTHY                                                              $
+SP1    -1.0
$                                                                         $
PANLST2 1000    1000    1000    1001    1002    1003    1004    1005    +P1
+P1     1006    1007
$                                                                         $
$       SID     G1      G2      ETC                                       $
SET1    1000    98      99
$ CORD2R DEFINES THE Y-AXIS FOR THE BEAM SPLINE                           $
$       CID     CS      A1      A2      A3      B1      B2      B3
CORD2R  1       0       15.     0.      0.      15.0    0.      10.     +CRD2
$       C1      C2      C3                                                $
+CRD2   20.     0.      10.
$                                                                         $
$ VERTICAL FIN SPLINE TO STRUCTURE GRIDS (100, 310, 311, 312)             $
```

```
$       EID     MODEL   CP      SETK    SETG    DZ      EPS
SPLINE1 1701    FIN             3100    3100    0.
PANLST2 3100    3100    3100    THRU    3115
SET1    3100    100     311     310     312
$                                                                       $
$                                                                       $
$                                                                       $
$                       * TRIM CONDITIONS *                             $
$                                                                       $
$                                                                       $
$                                                                       $
$        TRIM CONDITION 1: STEADY ROLL CONDITION                        $
$                                                                       $
$***********************************************************************$
$       TRIMID  IDMK    QDP     TRMTYP  EFFID   VO
$***********************************************************************$
TRIM    1       90      1200.                   1.0                     +TR1
$       LABEL1  VAL1    LABEL2  VAL2    LABEL3  VAL3    LABEL4  VAL4
+TR1    AILERON 25.0    BETA    FREE    RACCEL  0.0     PACCEL  0.0     +TR2
+TR2    RRATE   0.      RUDDER  FREE    PRATE   FREE    NY      0.0
$***********************************************************************$
$                               * * *                                   $
$        TRIM CONDITION 2: ABRUPT ROLL CONDITION                        $
$                                                                       $
$***********************************************************************$
$       TRIMID  IDMK    QDP     TRMTYP  EFFID   VO
$***********************************************************************$
TRIM    2       90      1200.                   1.0                     +TR1
$       LABEL1  VAL1    LABEL2  VAL2    LABEL3  VAL3    LABEL4  VAL4
+TR1    AILERON 25.0    BETA    FREE    RACCEL  0.0     PACCEL  FREE    +TR2
+TR2    RRATE   0.      RUDDER  FREE    PRATE   0.0     NY      0.0
$***********************************************************************$
ENDDATA
```

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4.0 ANALYSIS AND OPTIMIZATON CASES

GAF WING MODEL

4.1 Case 1.a: GAF (Generalized Advanced Fighter) Wing Model Analysis

- ***Purpose:*** To test a public domain model in static, normal modes, and flutter analysis.

- ***Description of input and results:***

The GAF model was an aircraft wing model composed of skins, spars, and ribs. A leading edge flap and a trailing edge control surface were attached to the main wing box. The wing was fixed at the root. More details about the model, the test cases, and their application to this model are given in Appendix A.

4.1.1 GAF Structural Configuration and Static Analysis

The structural configuration of the wing in the form of a FEM model is shown in Fig 4.1.1. Skins, spars, and ribs were modeled by **CQUAD4** elements, and **CELAS2** elements were used to connect the control surfaces to the wing box. A summary of the number of elements and grid points is shown in the following:

NUMBER OF GRID POINTS	288
NUMBER OF ELEMENTS	530
CROD	136
CELAS2	2
CQUAD4	371
RBE2	21

A static analysis was performed for applied static loads, distributed at given grid points, in the vertical direction, using **FORCE** cards. The wing was fixed as a cantilever by **SPC** cards. The identification number the of **FORCE** cards in the bulk data deck was called by a **STATIC** card and the ID number of the **SPC** cards in the bulk data deck was called by a BOUNDARY card in the case control deck. Displacements at grid points and stresses in elements were calculated, and the output print of these data was controlled by a PRINT card in the case control deck.

The weight of this structure was 671.60 *lbs*, and the associated weight data of the initial structure are shown in Table 4.1.1. To print out these weight data, a **GPWG** bulk data card was entered in the bulk data deck, and the associated ID number was called in the PRINT card of the case control deck. The six components of the displacement were printed. The maximum vertical displacement at the wing tip was 27.068 *in.* All stress components and the principal stresses were printed. The maximum principal stress in all elements was 64,000 *psi.* The data were used later as constraints in the structural design optimizations. The deformed shape of the structure is shown in Fig 4.1.2.

4.1.2 Aerodynamic Configuration and Analysis by ENSAERO

Aerodynamic analyses of the wing were performed by the CFD code, ENSAERO. The steady aerodynamic pressure coefficients calculated here were used later as input data for ZTAIC of ASTROS*. The steady aerodynamic pressure coefficients were calculated for Euler flow and also for Navier-Stokes flow, with the results of the Euler flow, via a **RESTART** statement. For all cases, the Reynolds number was 10,000,000 and spanwise and normal viscous terms were used. For turbulence, the Baldwin-Lomax turbulence model was used, and, for correction for vortex flow, Degani-Schiff modeling was used. Iteration indices were less than 1.0E-09 and iteration numbers were about 500 for the Euler flow and then more than 500 additional iterations for the Navier-Stokes flow. The aerodynamic configuration of the wing is shown in Fig 4.1.3. The total number of grid points was 151 x 44 x 34 in the x-, y-, and z- directions, respectively. The number of grid points on the wing was 61 x 34 on both lower and upper surfaces. The total number of iterations for Euler flow plus Navier-Stokes flow was about 1000, and the total CPU time on the CRAY computer was about 2 hours. In the transonic region belonged $M = 0.85$, convergence was slower than in the other regions, and more iterations were needed.

Two Mach number cases, $M = 0.85$ and $M = 0.90$, and two angle-of-attack (α)cases, α=0.0° and α=5.0°, for a total of four cases were investigated. The results of the calculated aerodynamic pressure coefficients for Euler flow and for Navier-Stokes flow are shown in Fig 4.1.4. In Euler flow, the strength of the shock was larger than in Navier-Stokes flow. This seems to come about because of the viscous effects in the Navier-Stokes flow. The computed points were as follows:

(1) $M = 0.85$, $\alpha = 0.0°$ (Navier-Stokes Flow)
(2) $M = 0.85$, $\alpha = 5.0°$ (Navier-Stokes Flow)
(3) $M = 0.90$, $\alpha = 0.0°$ (Navier-Stokes Flow)
(4) $M = 0.90$, $\alpha = 5.0°$ (Navier-Stokes Flow)

Fig 4.1.4 shows that the flows were in the transonic regime at $M = 0.85$ and $M = 0.90$.

4.1.3 Normal Modes Analysis Using ASTROS*

Natural frequencies, the associated modes shapes, and the generalized stiffness and mass matrices were calculated in the normal modes discipline. For the calculation of the eigenvalues, the INV (Inverse Power) method was used. This method was selected via the **EIGR** bulk data card and the ID number of this card was called by METHOD in the BOUNDARY card in the case control deck. **ASET** cards were used to save computing time and neglect motions other than vertical. Mode normalization was used in MASS because it was convenient that the components of the generalized mass were unity.

Normal modes data for 8 modes from the lowest mode up to 90.0 *Hz* were calculated. The lowest eight natural frequencies of the GAF model were 10.22, 30.97, 35.89, 49.74, 58.04, 65.51, 76.09, and 84.75 *Hz*. The results are shown in Table 4.1.2 and the mode shapes are presented in

Fig 4.1.5. The first and second modes were bending modes and the third mode was the first torsion mode. These data were later used in the flutter calculations. The lowest natural frequency, 10.22 *Hz*, was used as a constraint in normal modes design optimization.

4.1.4 Flutter Analysis

Flutter analyses were performed by the K-method in ASTROS*, the P-K method in MSC/NASTRAN, and the root-locus method outside of these codes in three aerodynamic regimes: transonic, low supersonic, and high supersonic/hypersonic. Mach numbers M=0.85, 1.15, and 3.0 were selected to calculate flutter speeds. ZONA6 and ZTAIC of ASTROS* were used to calculate generalized unsteady aerodynamic loads at M=0.85, and ZONA7 and ZONA7U were used for M=1.15 and M=3.0, respectively. The results are compared with those for MSC/NASTRAN and the root-locus method in Table 4.1.3. The generalized unsteady aerodynamic loads calculated by ASTROS* were used in the root-locus method. Two **CAERO7** cards were used: the **CAERO7,** 100001 card represented the wing with 15 x 11 aerodynamic boxes. The **CAERO7,** 200001 card represented the fuselage region with 15 x 2 aerodynamic boxes.

The generalized unsteady aerodynamic loads at M=0.85 were calculated by ZONA6. There were 8 x 8 generalized aerodynamic coefficient terms, Q_{ij}, for each reduced frequency k. The plots of the real and imaginary parts of Q_{1j} and Q_{2j} (j = 1, 2,.. 8) versus k are shown in Fig 4.1.6. Generalized unsteady aerodynamic loads were also approximated by the minimum-state method at M=0.85. In Fig 4.1.7, the Q_{1j} and Q_{2j} calculated by ZONA6 are shown as real part versus imaginary part by black and solid lines and the approximate Q_{1j} and Q_{2j} calculated by the minimum-state method are shown by color and dotted lines. The V-f and V-g plots for the results by ZONA6 of ASTROS* are shown in Fig 4.1.8. The flutter speed was 17,337 *in/sec* and the flutter frequency was 14.3 *Hz*. The root-locus plot to calculate the flutter speed is shown in Fig 4.1.9. The flutter speed was 15,888 *in/sec* and the flutter frequency was 17.3 *Hz*. The plots of Figs 4.1.10 – 4.1.13 are for the results by ZTAIC at M=0.85. The flutter speed and flutter frequency were 18,172 *in/sec* and 18.1 *Hz*, respectively, by the K-method, and 16,581 *in/sec* and 15.6 *Hz* by the root-locus method. It is normally expected that the nonlinear flutter speed is lower than the linear flutter speed in the transonic regime. However, for the case of the GAF model, the nonlinear flutter speed was slightly higher than the linear flutter speed. The plots of Figs 4.1.14 – 4.1.17 are for the results by ZONA7 at M=1.15. The flutter speed and flutter frequency were 20,776 *in/sec* and 19.8 *Hz*, respectively, by the K-method, while a divergence speed 14,170 *in/sec* was obtained by the root-locus method. The plots of Figs 4.1.18 – 4.1.21 are for the results by ZONA7U at M=3.0. The flutter speed and flutter frequency were 31,743 *in/sec* and 21.1 *Hz*, respectively, by the K-method and 33,536 *in/sec* and 21.3 *Hz* by the root-locus method. For subsonic flow at M=0.85 and supersonic flow at M=1.15, the root-locus results were close to the MSC/ NASTRAN results as shown in Table 4.1.3.

Table 4.1.1 Weight Data Output of GAF Model.

```
              OUTPUT FROM GRID POINT WEIGHT GENERATOR
                        REFERENCE POINT =       1
         XO = 3.685130E+01, YO = 0.000000E+00, ZO = 2.084700E+00
                                  M O
* 6.7160E+02  0.000E+00  0.0000E+00  0.0000E+00 -1.405E+03 -4.1995E+04 *
* 0.0000E+00  6.716E+02  0.0000E+00  1.4051E+03  0.000E+00  2.8357E+04 *
* 0.0000E+00  0.000E+00  6.7160E+02  4.1995E+04 -2.835E+04  0.0000E+00 *
* 0.0000E+00  1.405E+03  4.1995E+04  3.6085E+06 -2.140E+06  5.7740E+04 *
*-1.4051E+03  0.000E+00 -2.8357E+04 -2.1406E+06  1.635E+06  8.8539E+04 *
*-4.1995E+04  2.835E+04  0.0000E+00  5.7740E+04  8.853E+04  5.2324E+06 *
                                  S
        *  1.00000E+00  0.00000E+00  0.00000E+00 *
        *  0.00000E+00  1.00000E+00  0.00000E+00 *
        *  0.00000E+00  0.00000E+00  1.00000E+00 *
DIRECTION
MASS AXIS SYSTEM (S)  MASS          X-C.G.        Y-C.G.        Z-C.G.
        X          6.71602E+02   0.00000E+00   6.25301E+01  -2.09224E+00
        Y          6.71602E+02   4.22239E+01   0.00000E+00  -2.09224E+00
        Z          6.71602E+02   4.22239E+01   6.25301E+01   0.00000E+00
```

Table 4.1.2 Results of Normal Modes Analysis of GAF Model.

Mode	Eigenvalue (rad/s^2)	Freq. ($Hz.$)	Generalized Mass	Generalized Stiffness
1	4.12692E+03	1.02243E+01	1.00000E+00	4.12692E+03
2	3.78674E+04	3.09708E+01	1.00000E+00	3.78674E+04
3	5.08536E+04	3.58906E+01	1.00000E+00	5.08536E+04
4	9.76608E+04	4.97371E+01	1.00000E+00	9.76608E+04
5	1.32991E+05	5.80406E+01	1.00000E+00	1.32991E+05
6	1.69421E+05	6.55094E+01	1.00000E+00	1.69421E+05
7	2.28595E+05	7.60945E+01	1.00000E+00	2.28595E+05
8	2.83559E+05	8.47504E+01	1.00000E+00	2.83559E+05

Table 4.1.3 Results of Flutter Analyses of GAF Model.

No	Mach	Method	Flutter Speed (*in/sec*)	F. Freq. (*Hz*)	Remarks
1	0.85	ZONA6	17,336	14.3	
		ZTAIC	18,172	18.1	
		MSC/NASTRAN	15,800	16.7	
		Root-locus (ZONA6)	15,888	17.3	
		Root–locus (ZTAIC)	16,581	15.6	
2	1.15	ZONA7	20,776	19.8	
		MSC/NASTRAN	14,500	0.0	Divergence
		Root-locus (ZONA7)	14,170	0.0	Divergence
3	3.0	ZONA7U	31,743	21.1	
		MSC/NASTRAN	36,100	22.0	
		Root-locus (ZONA7U)	33,536	21.3	

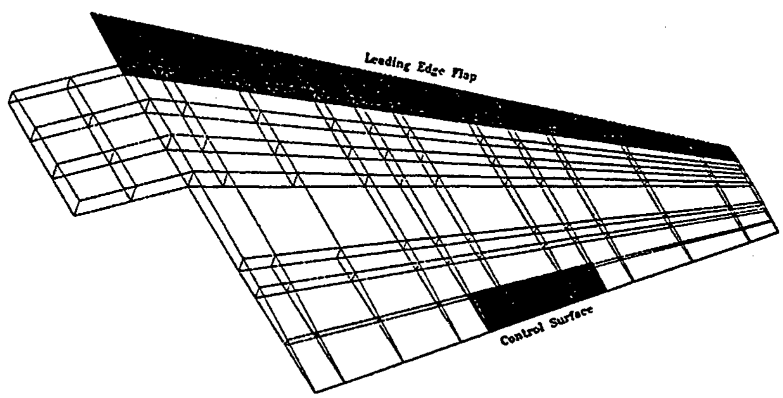


Figure 4.1.1 Structural Configuration of GAF Model by FEM.

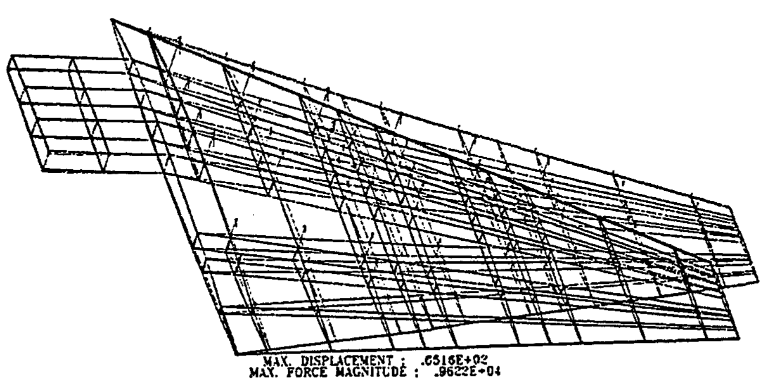


Figure 4.1.2 Deflection Shape of GAF Model for Static Loads.

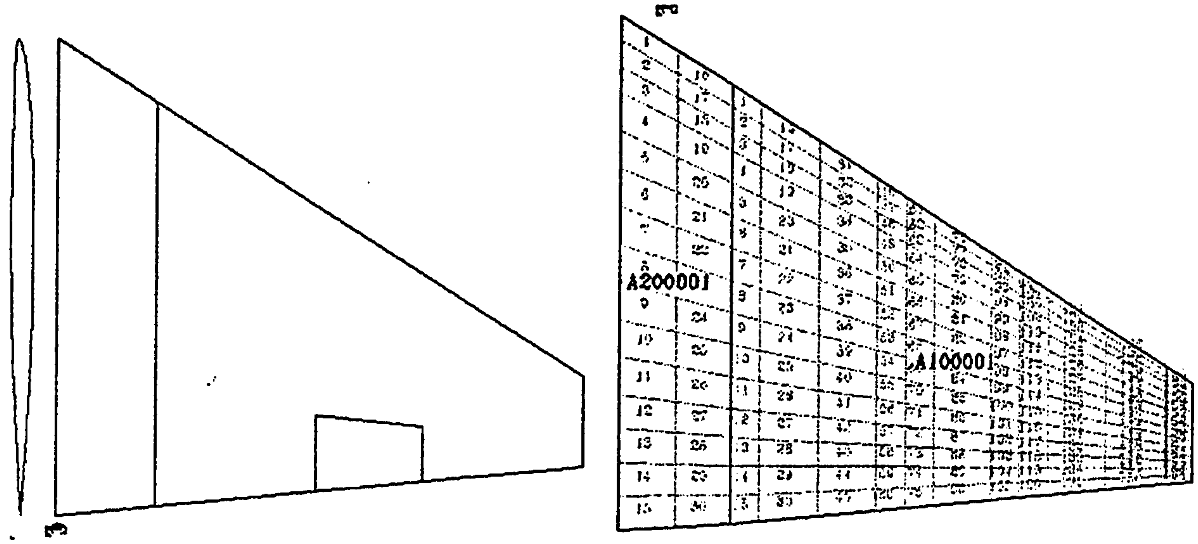


Figure 4.1.3 Aerodynamic Configuration of GAF Model and Aerodynamic Panels.

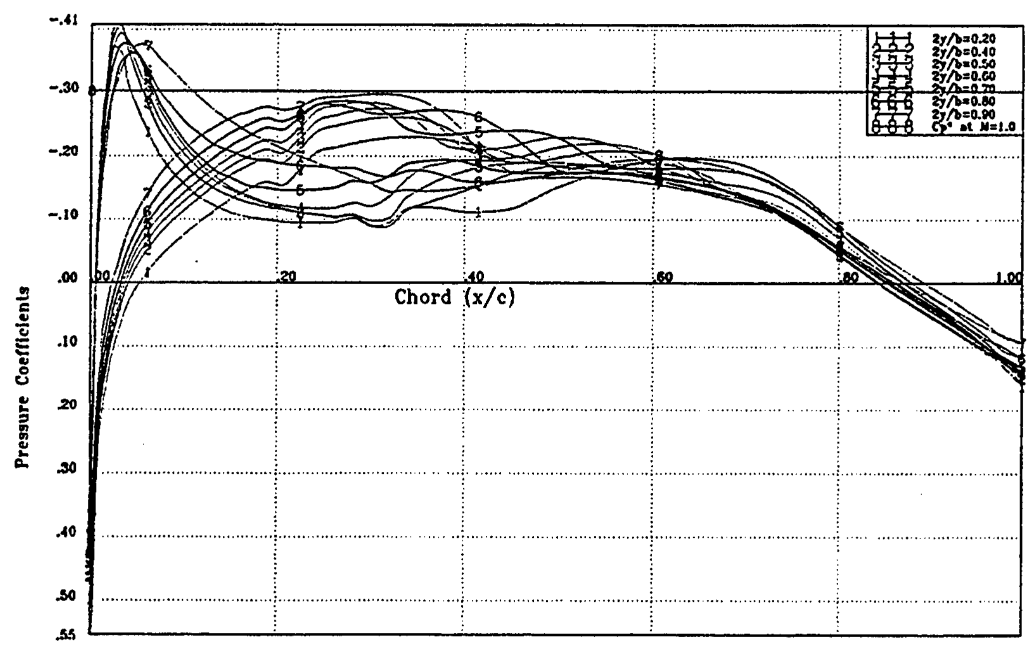


Figure 4.1.4.a Aerodynamic Pressure Coefficients of GAF Model for Navier-Stokes Flow: $M = 0.85$, AoA = 0.0°, by ENSAERO.

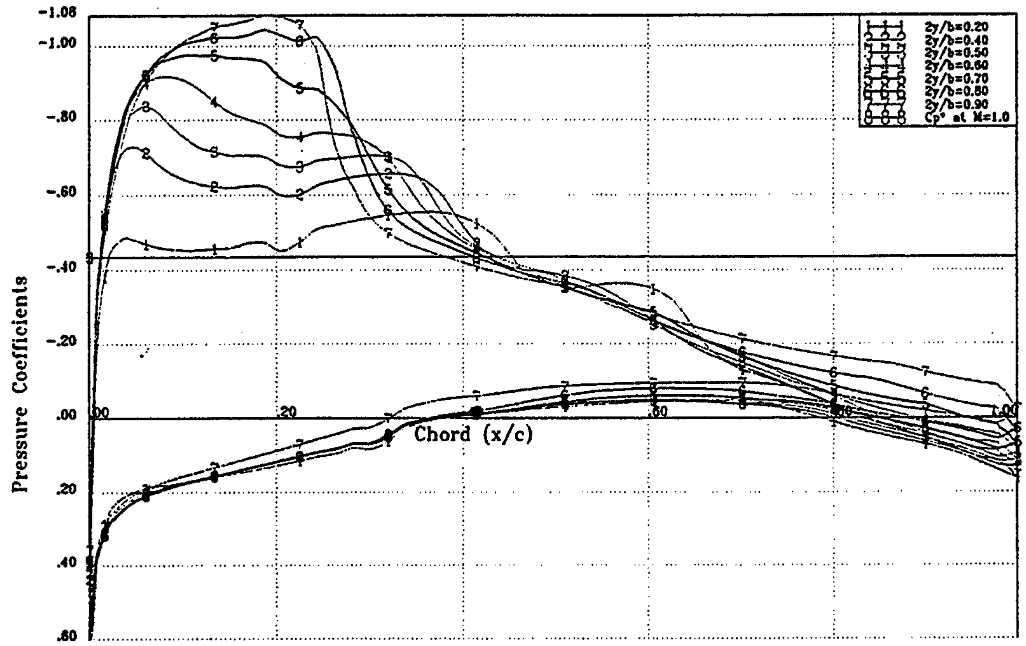


Figure 4.1.4.b Aerodynamic Pressure Coefficients of GAF Model for Navier-Stokes Flow: $M = 0.85$, AoA = 5.0°, by ENSAERO.

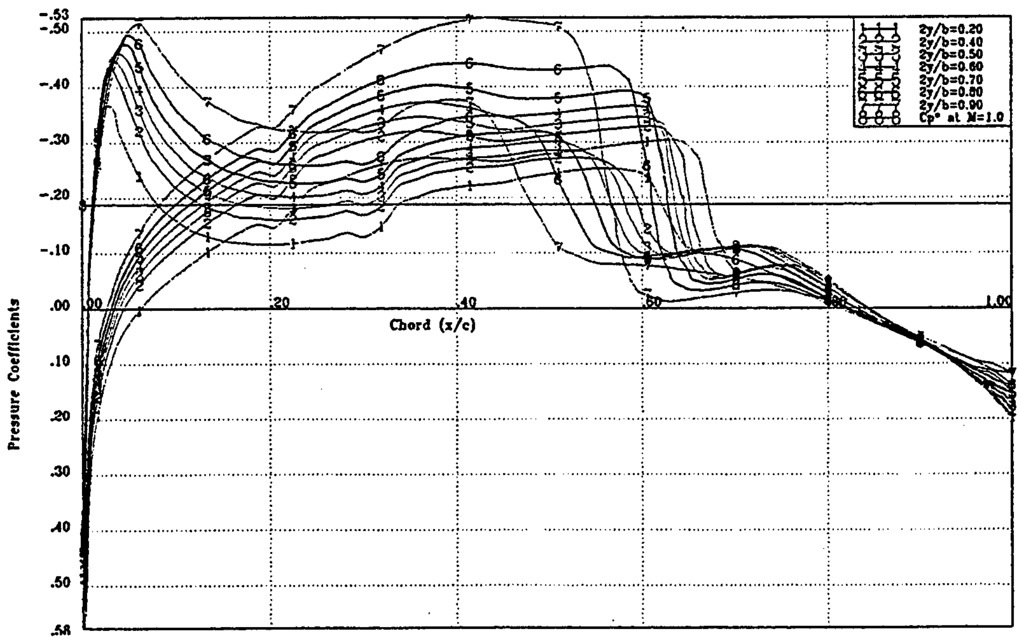


Figure 4.1.4.c Aerodynamic Pressure Coefficients of GAF Model for Navier-Stokes Flow: $M = 0.90$, AoA = 0.0°, by ENSAERO.

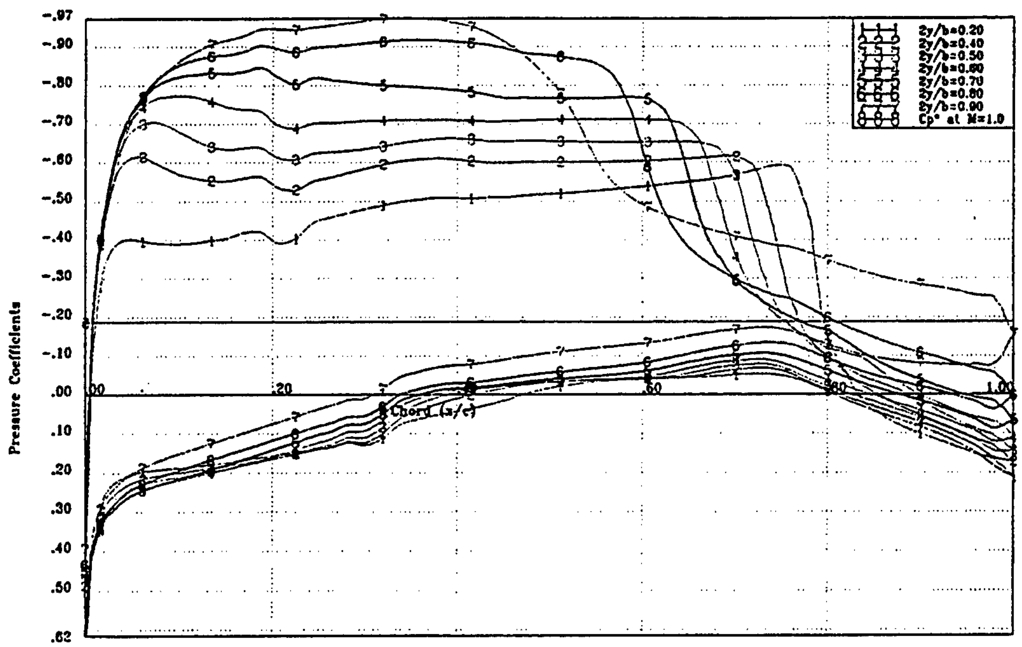


Figure 4.1.4.d **Aerodynamic Pressure Coefficients of GAF Model for Navier-Stokes Flow: $M = 0.90$, AoA = 5.0°, by ENSAERO.**

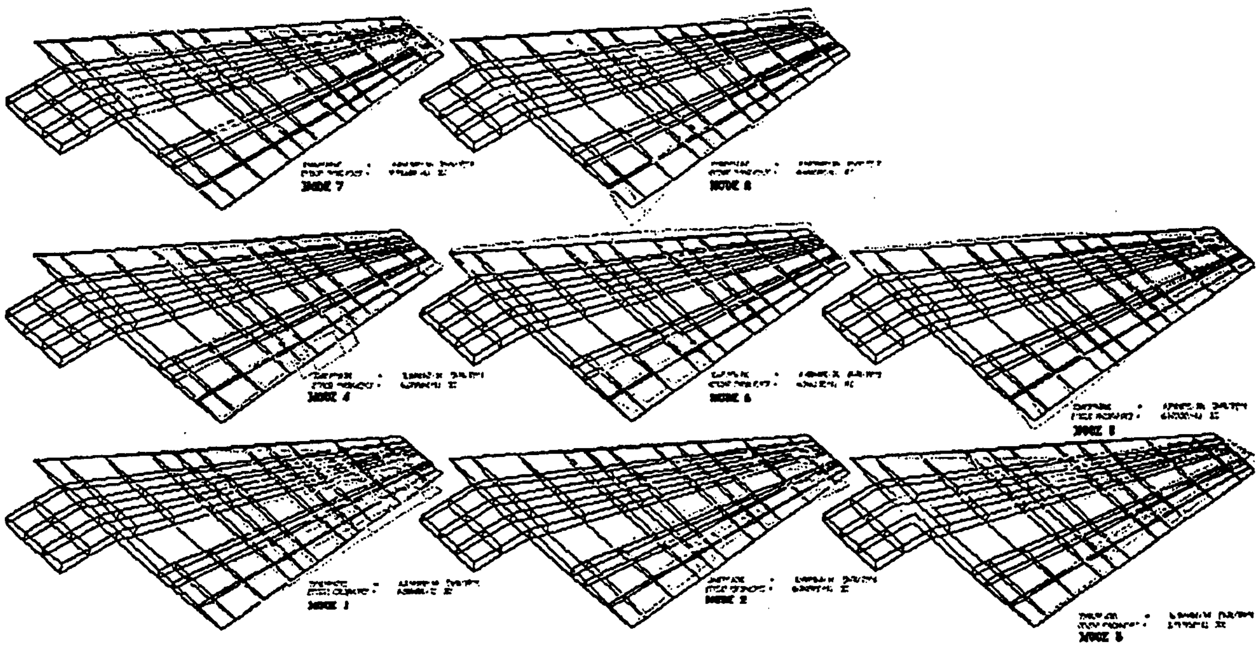


Figure 4.1.5 **Normal Modes of GAF Model.**

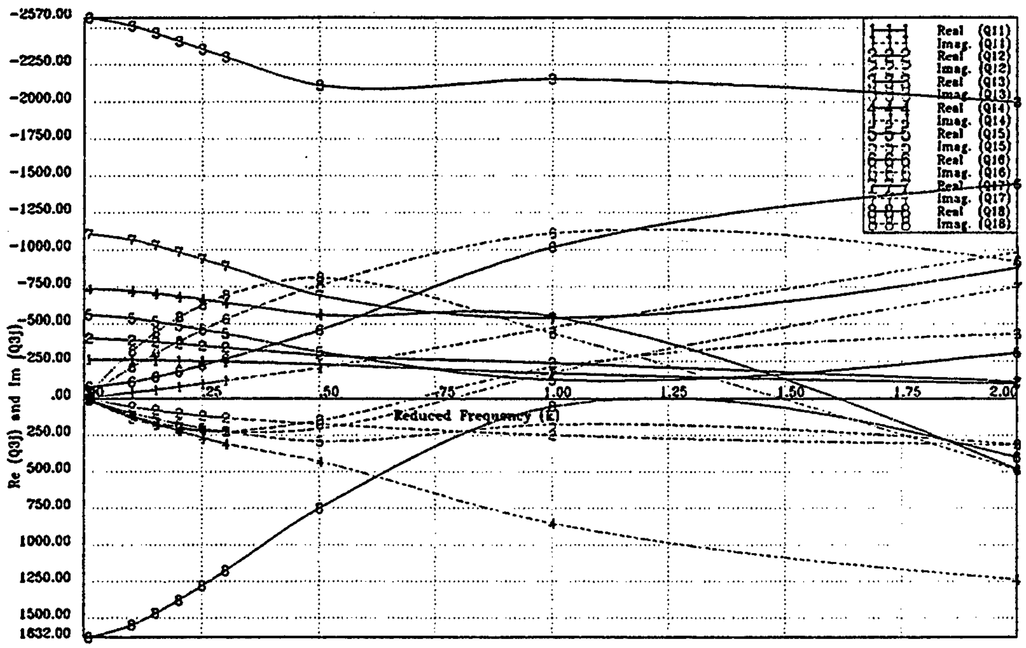


Figure 4.1.6.a Generalized Unsteady Aerodynamic Coefficients Q_{1j} of GAF Model: $M = 0.85$, by ZONA6 of ASTROS*.

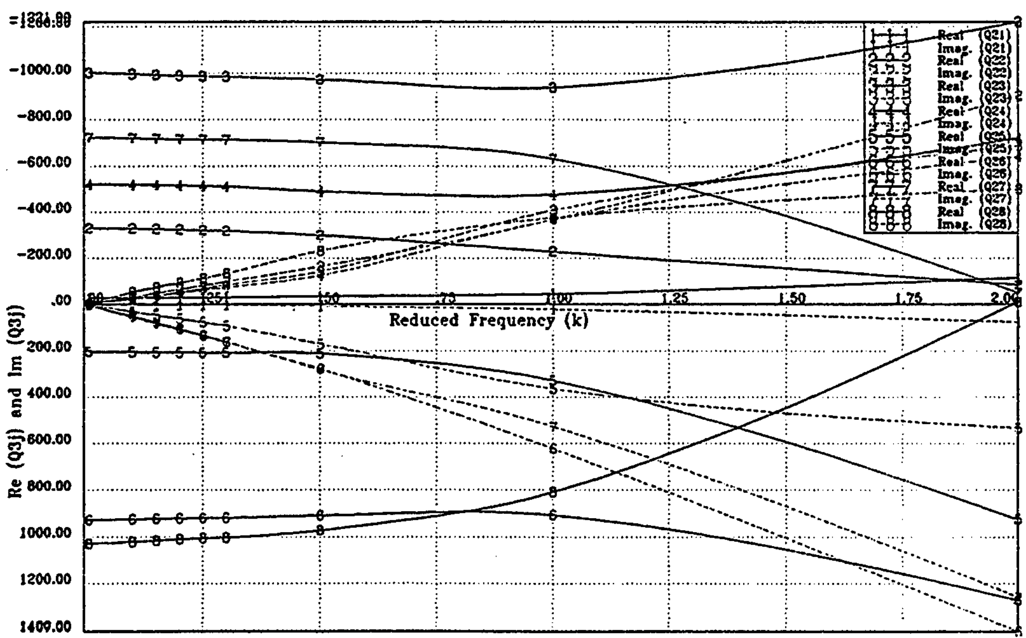


Figure 4.1.6.b Generalized Unsteady Aerodynamic Coefficients Q_{1j} of GAF Model: $M = 0.85$, by ZONA6 of ASTROS*.

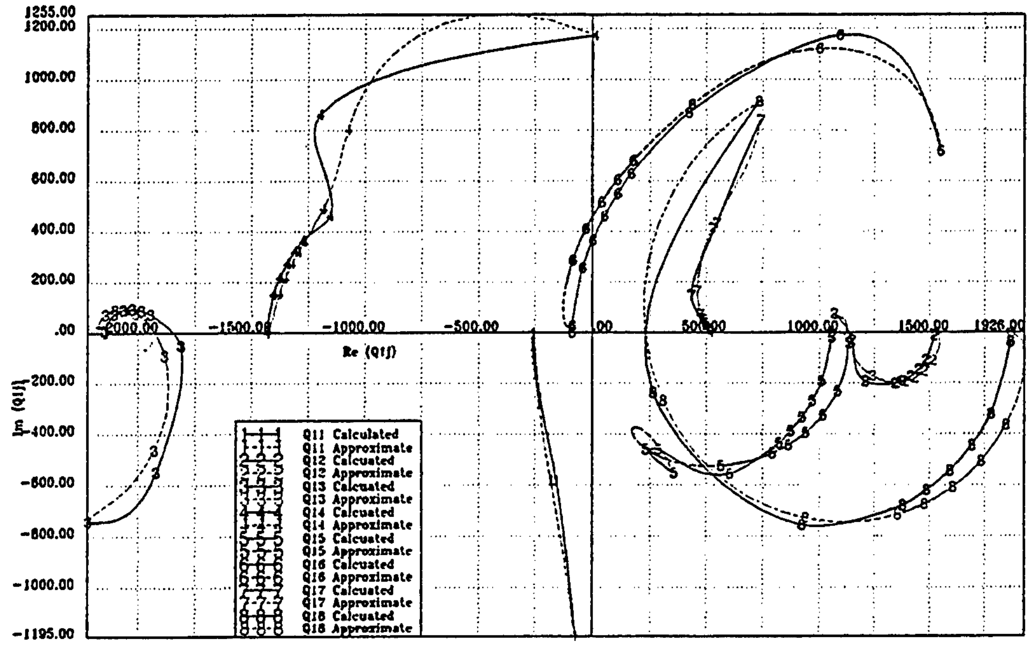


Figure 4.1.7.a Generalized Unsteady Aerodynamic Coefficients Q_{1j} of GAF Model: $M = 0.85$, by ZONA6 of ASTROS* and Approximated by Minimum-State Method.

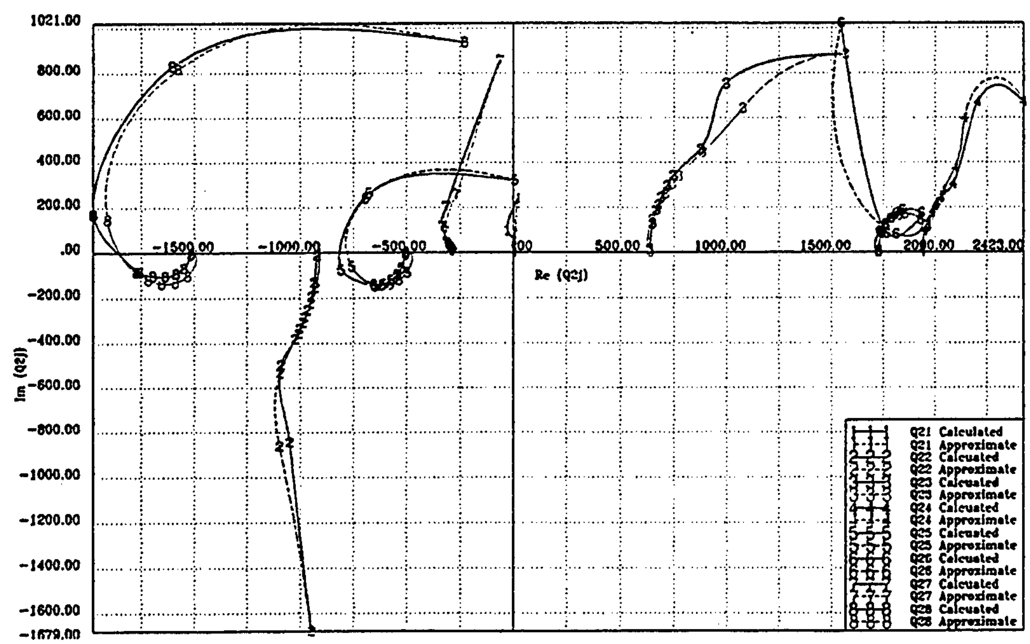


Figure 4.1.7.b Generalized Unsteady Aerodynamic Coefficients Q_{1j} of GAF Model: $M = 0.85$, by ZONA6 of ASTROS* and Approximated by Minimum-State Method.

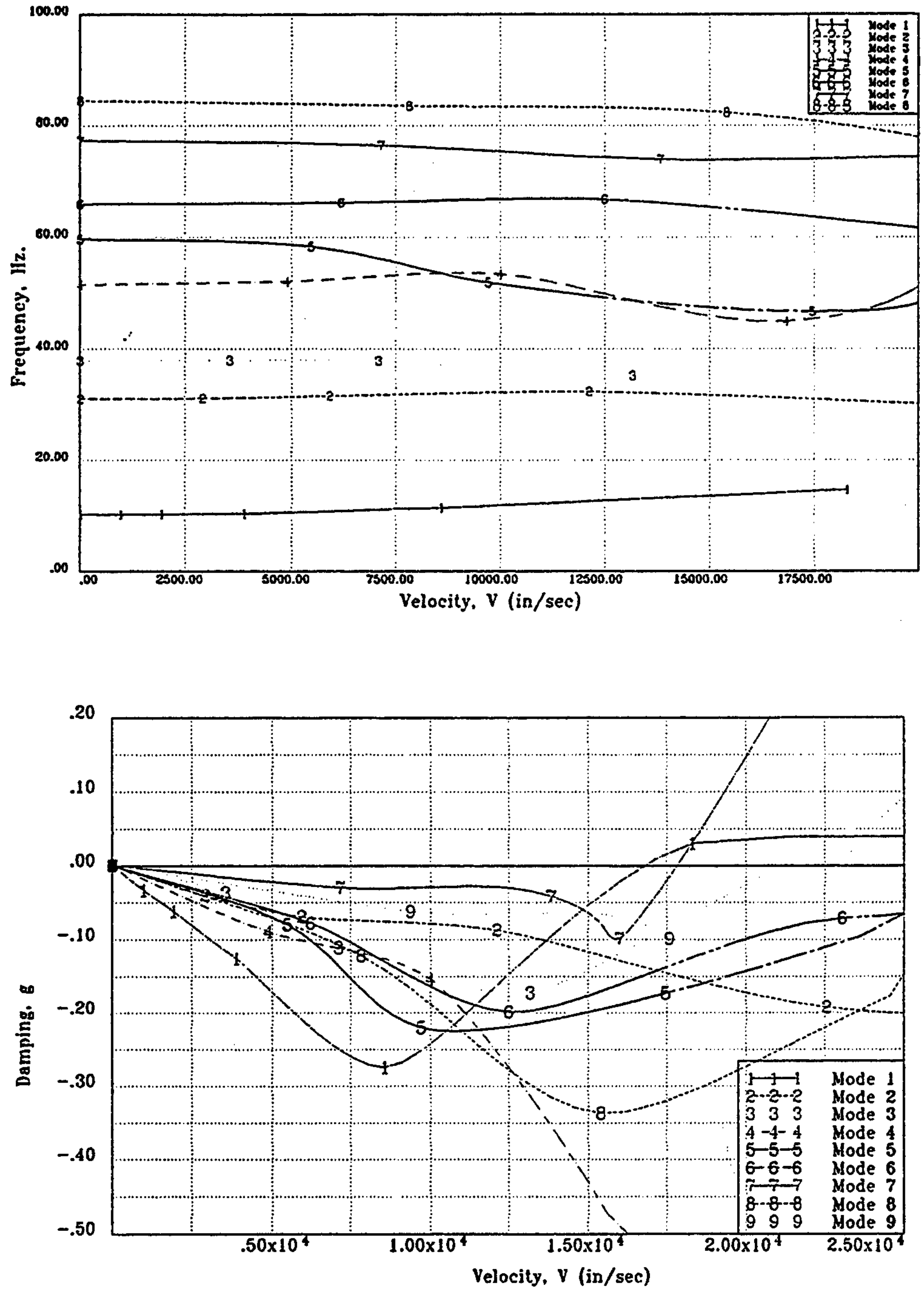


Figure 4.1.8 V-f and V-g Plots of GAF Model: $M = 0.85$, by ZONA6 of ASTROS*
(Flutter Speed = 17,337 *in/sec*, Flutter Frequency = 14.3 *Hz.*)

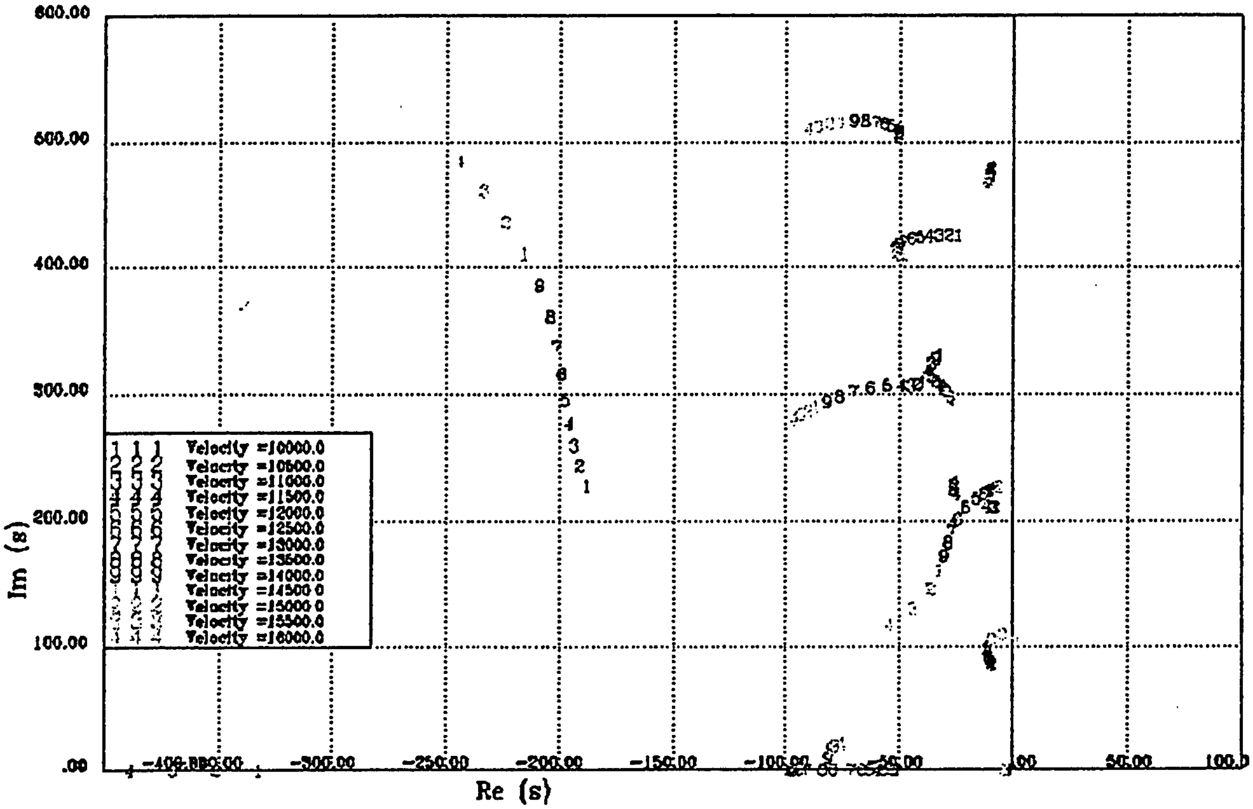


Figure 4.1.9 **Root-Locus Plot of GAF Model: $M = 0.85$, by ZONA6 of ASTROS***
(Flutter Speed = 15,888 *in/sec*, Flutter Frequency = 17.32 *Hz*).

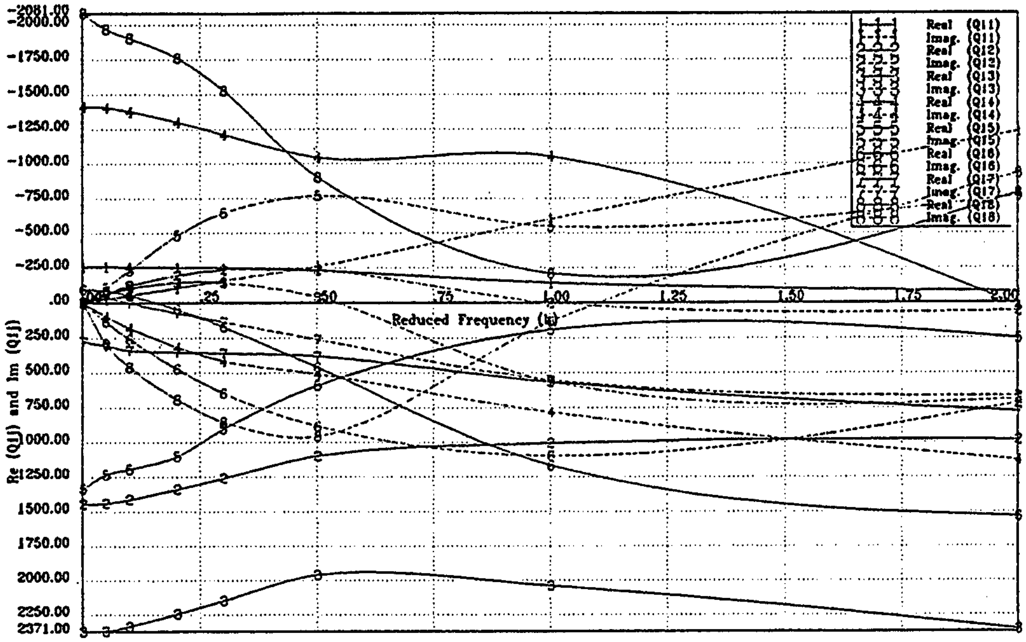


Figure 4.1.10.a **Generalized Unsteady Aerodynamic Coefficients Q_{1j} of GAF Model: M = 0.85, by ZTAIC of ASTROS*.**

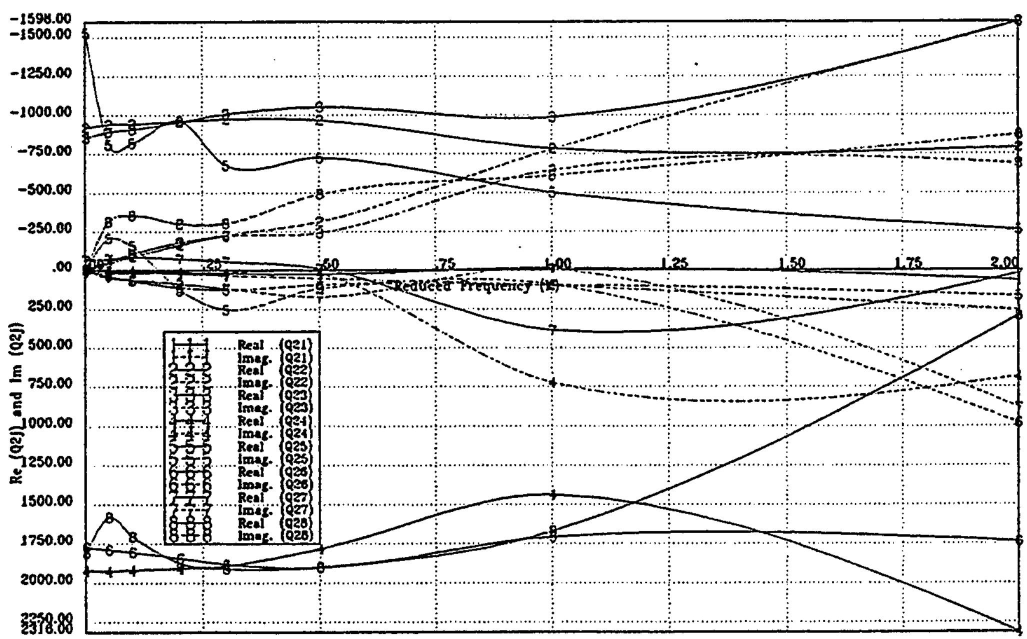


Figure 4.1.10.b **Generalized Unsteady Aerodynamic Coefficients Q_{1j} of GAF Model: M = 0.85, by ZTAIC of ASTROS*.**

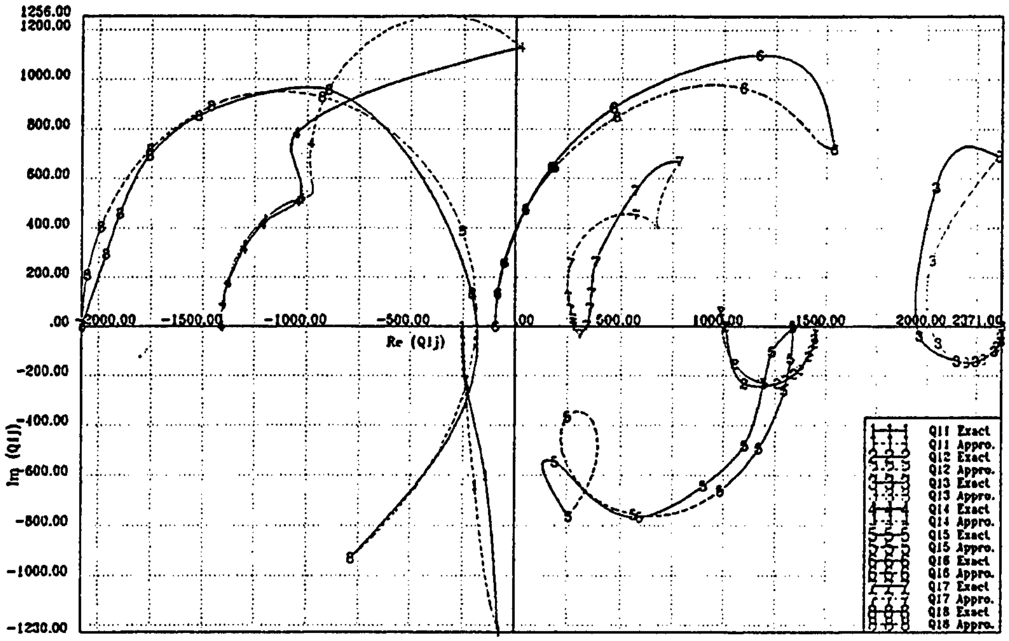


Figure 4.1.11.a Generalized Unsteady Aerodynamic Coefficients Q_{1j} of GAF Model: $M = 0.85$, by ZTAIC of ASTROS* and Approximated by Minimum-State Method.

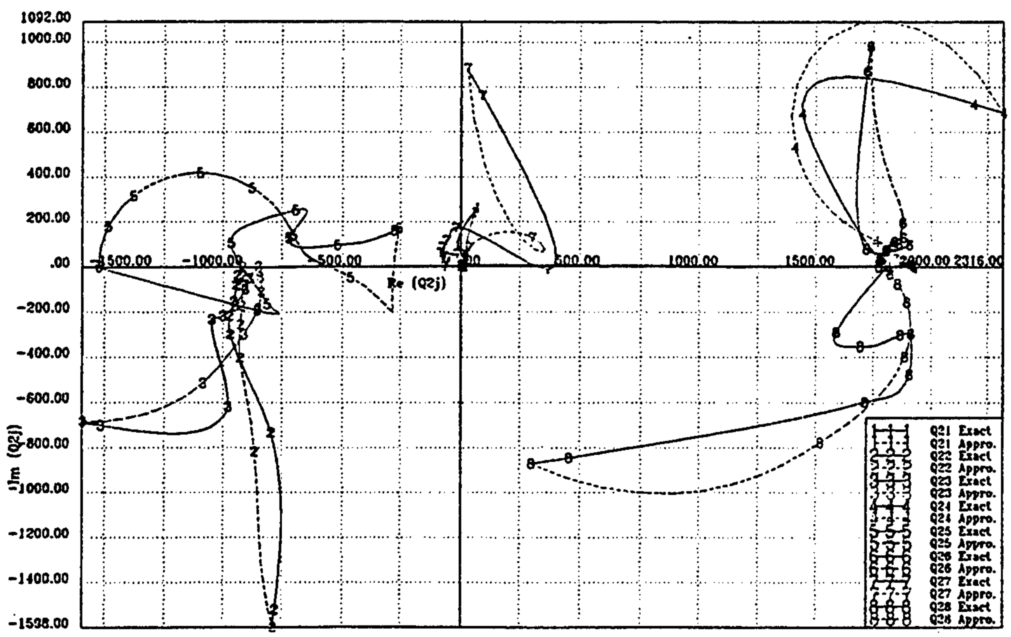


Figure 4.1.11.b Generalized Unsteady Aerodynamic Coefficients Q_{2j} of GAF Model: $M = 0.85$, by ZTAIC of ASTROS* and Approximated by Minimum-State Method.

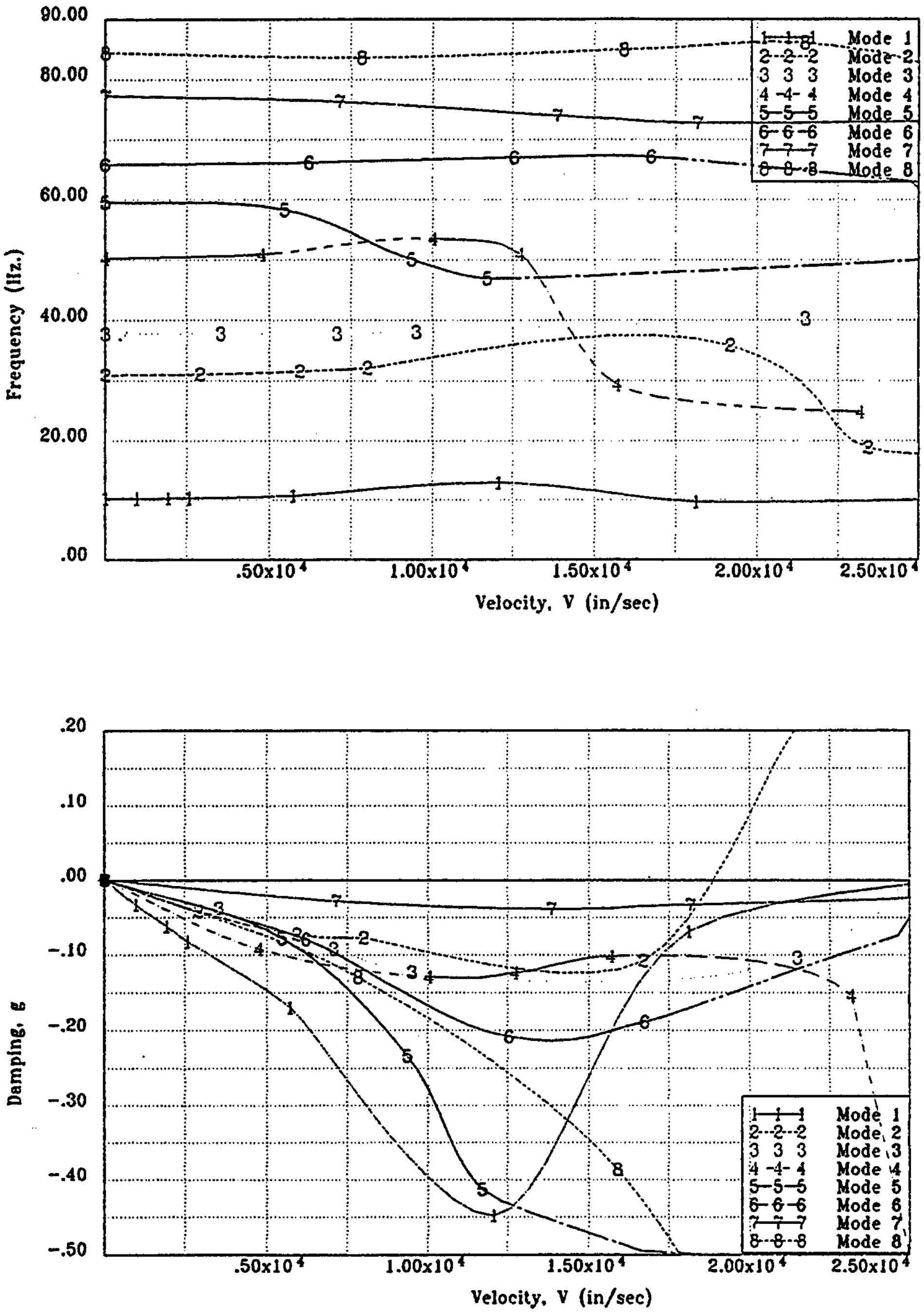


Figure 4.1.12 **V-f and V-g Plots of GAF Model: $M = 0.85$, by ZTAIC of ASTROS* (Flutter Speed = 18,172 *in/sec*, Flutter Frequency = 18.1 *Hz*).**

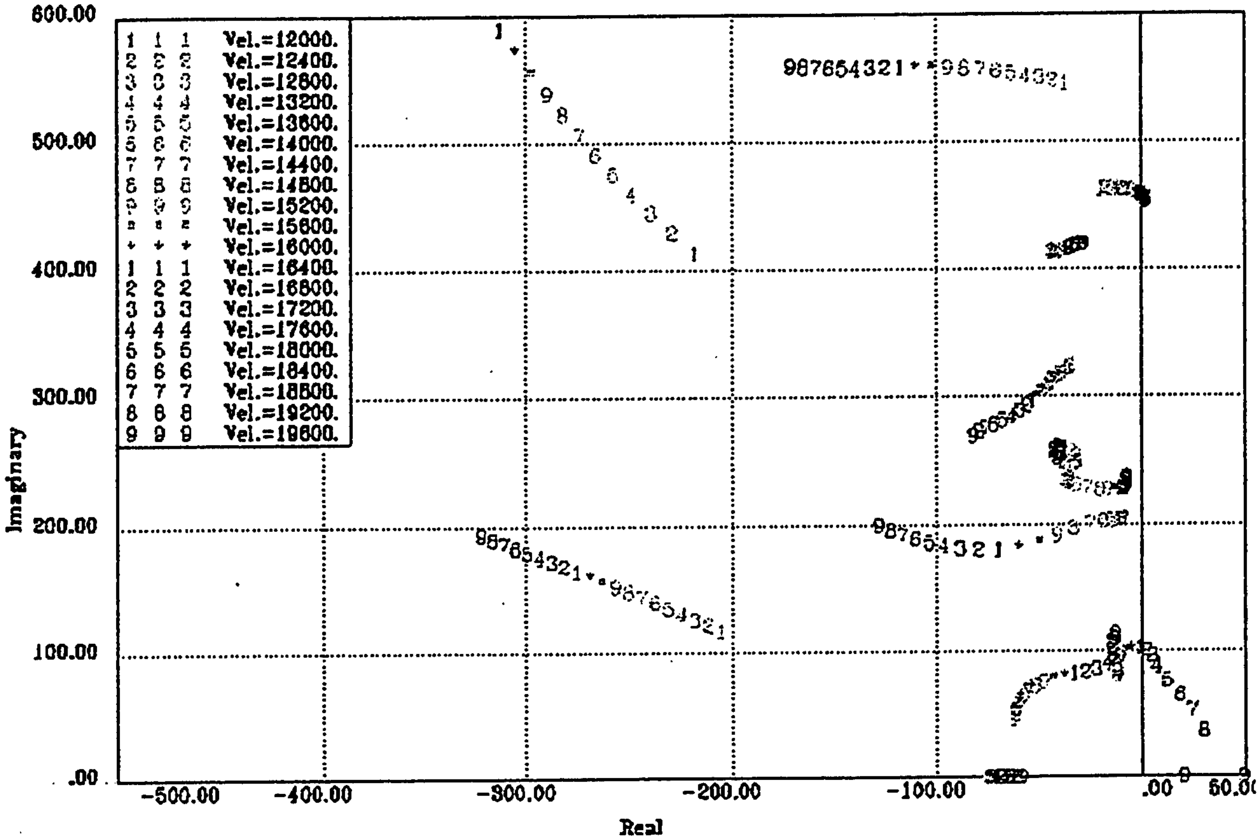


Figure 4.1.13 **Root-Locus Plot of GAF Model: M = 0.85, by ZTAIC of ASTROS***
(Flutter Speed = 16,581 *in/sec*, Flutter Frequency = 15.6 *Hz*).

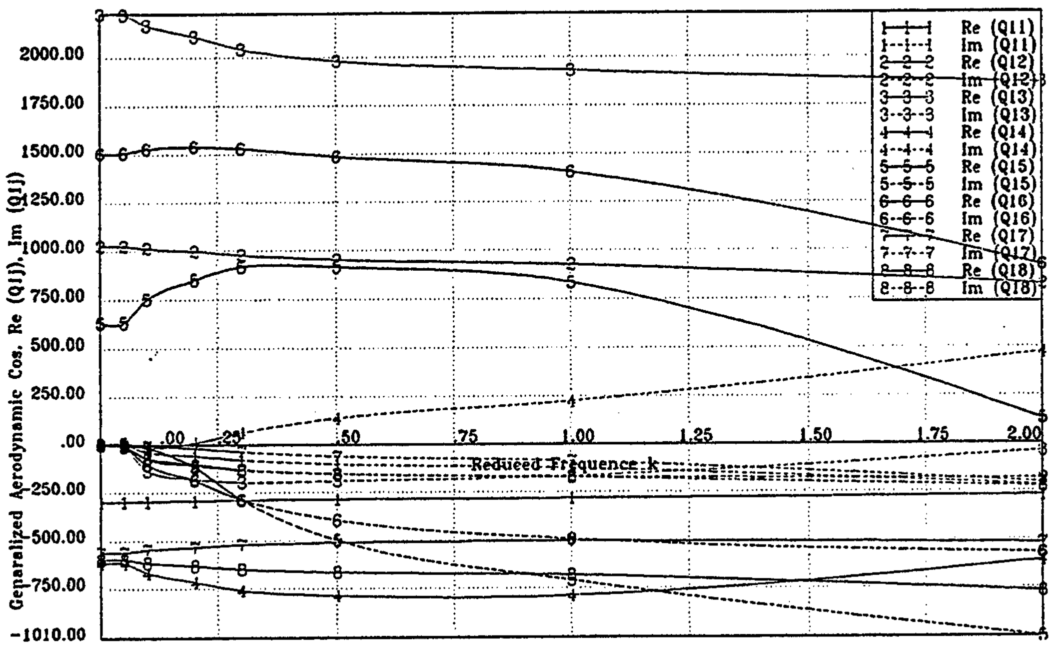


Figure 4.1.14 Generalized Unsteady Aerodynamic Coefficients Q_{1j} of GAF Model: $M = 1.15$, by ZONA7 of ASTROS*.

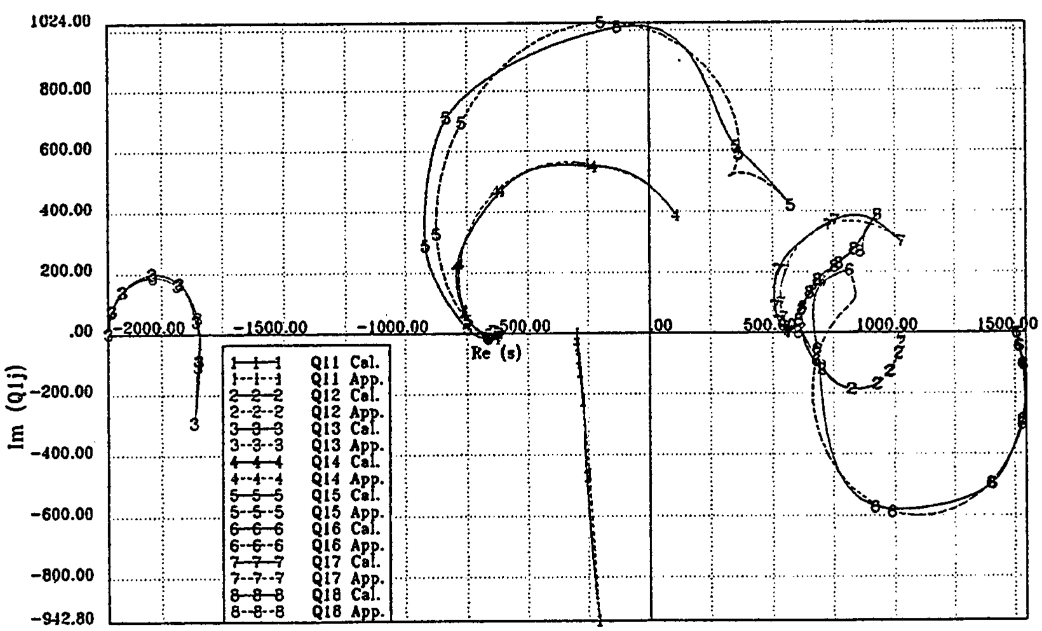


Figure 4.1.15 Generalized Unsteady Aerodynamic Coefficients Q_{1j} of GAF Model: $M = 1.15$, by ZONA7 of ASTROS* and Approximated by Minimum-State Method.

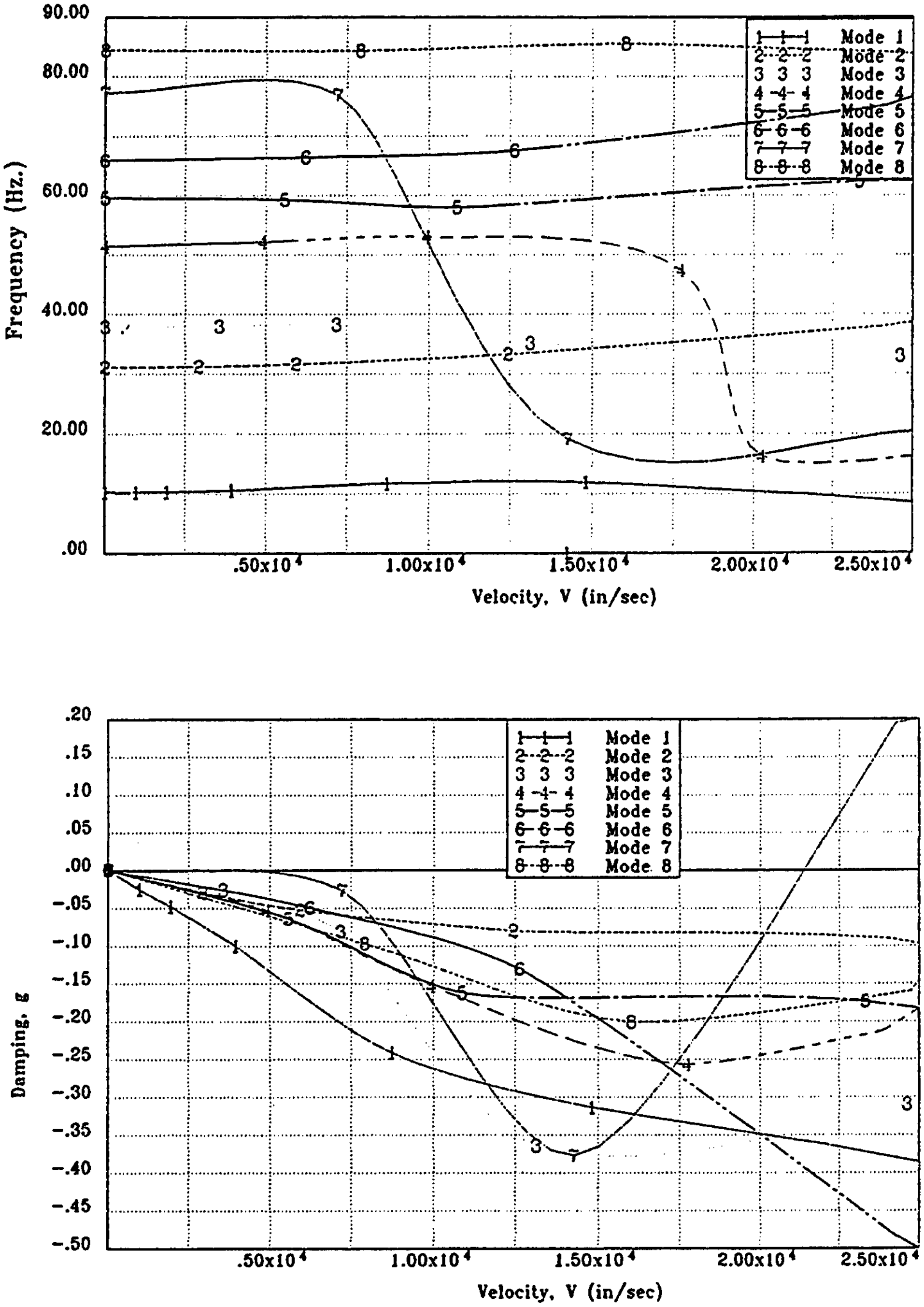


Figure 4.1.16 V-f and V-g Plots of GAF Model: $M = 1.15$, by ZONA7 of ASTROS*
(Flutter Speed = 20,776 *in/sec*, Flutter Frequency = 19.8 *Hz*).

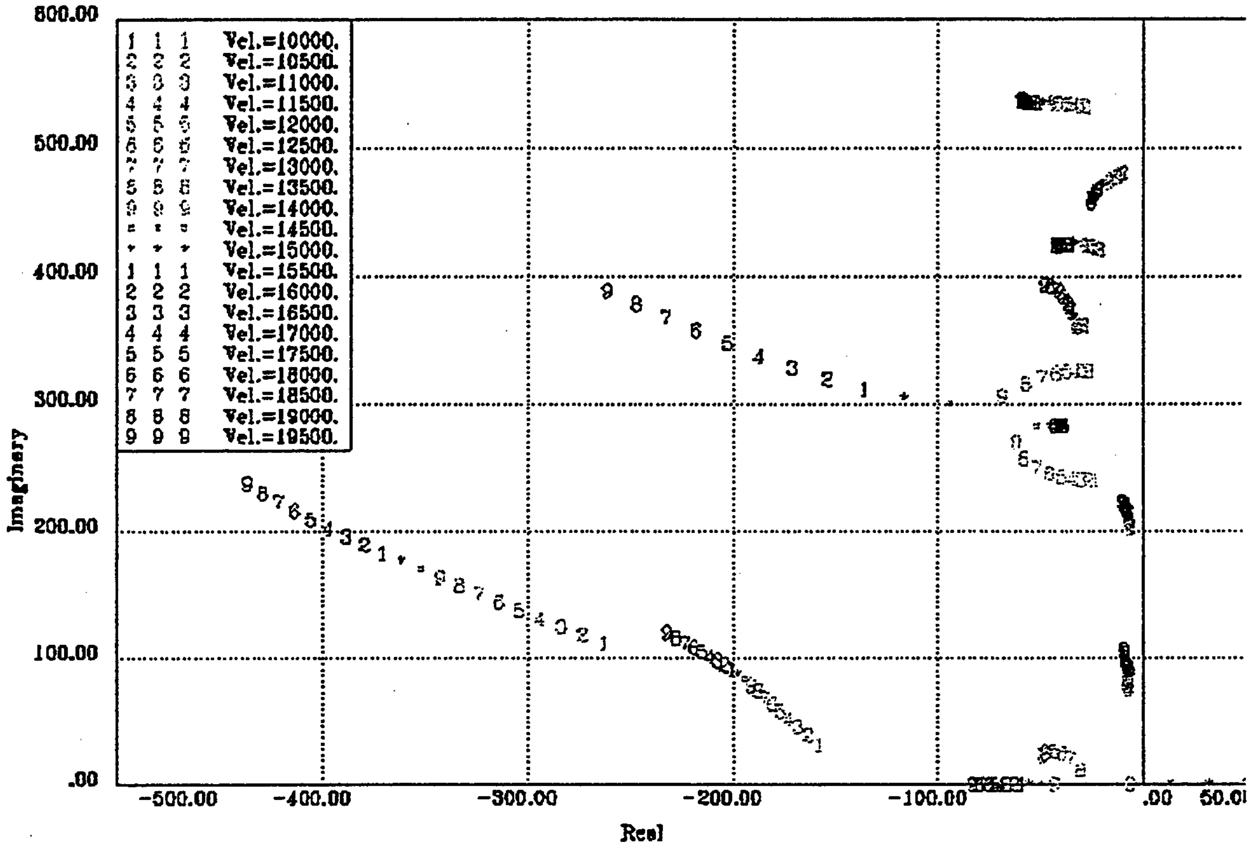


Figure 4.1.17 Root-Locus Plot of GAF Model: M = 1.15, by ZONA7 of ASTROS* (Divergence Speed = 14,170 *in/sec*, No Flutter).

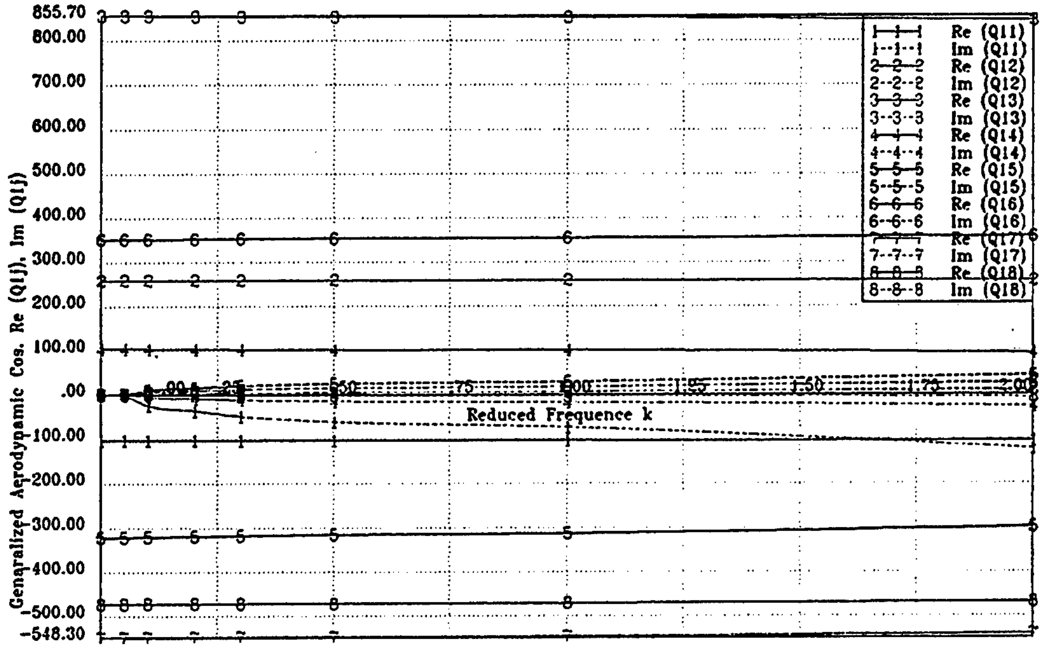


Figure 4.1.18 **Generalized Unsteady Aerodynamic Coefficients Q_{1j} of GAF Model: $M = 3.0$, by ZONA7U of ASTROS*.**

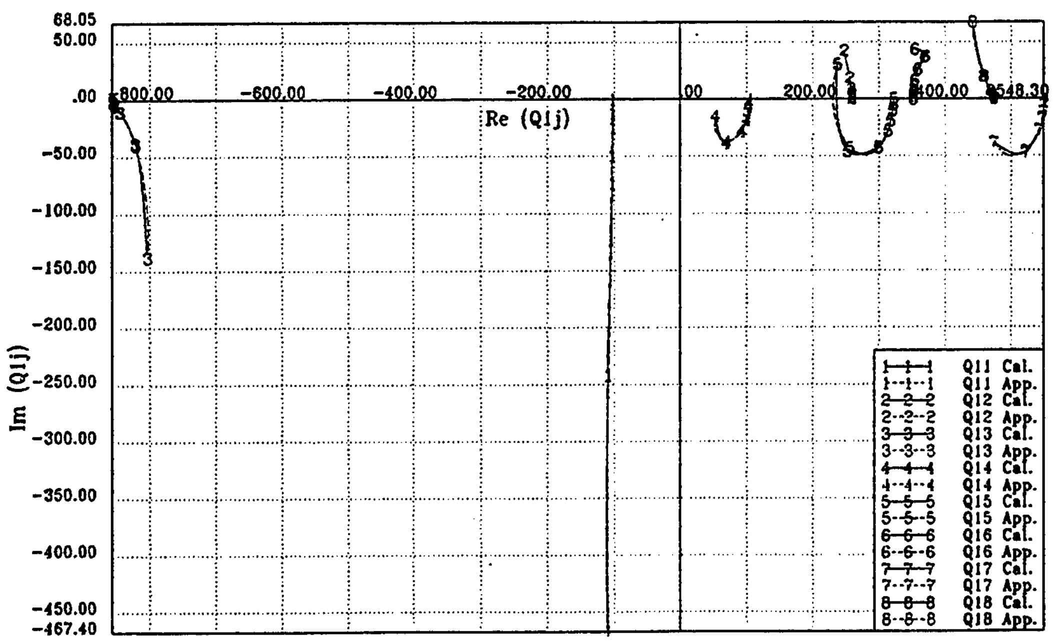


Figure 4.1.19 **Generalized Unsteady Aerodynamic Coefficients Q_{1j} of GAF Model: $M = 3.0$, by ZONA7U of ASTROS* and Approximated by Minimum-State Method.**

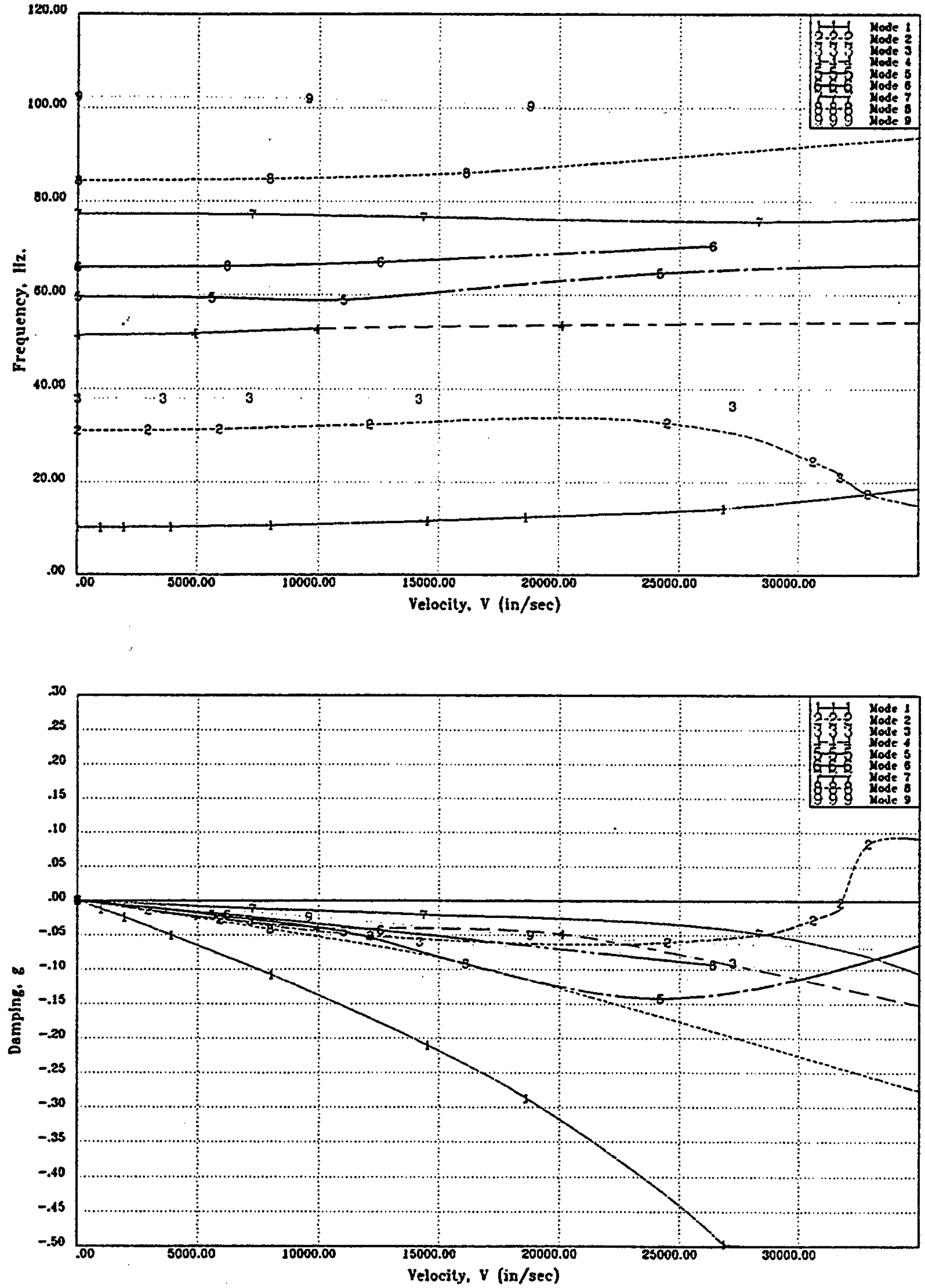


Figure 4.1.20 **V-f and V-g Plots of GAF Model: $M = 3.0$, by ZONA7U of ASTROS***
(Flutter Speed = 31,743 *in/sec*, Flutter Frequency = 21.1 *Hz*).

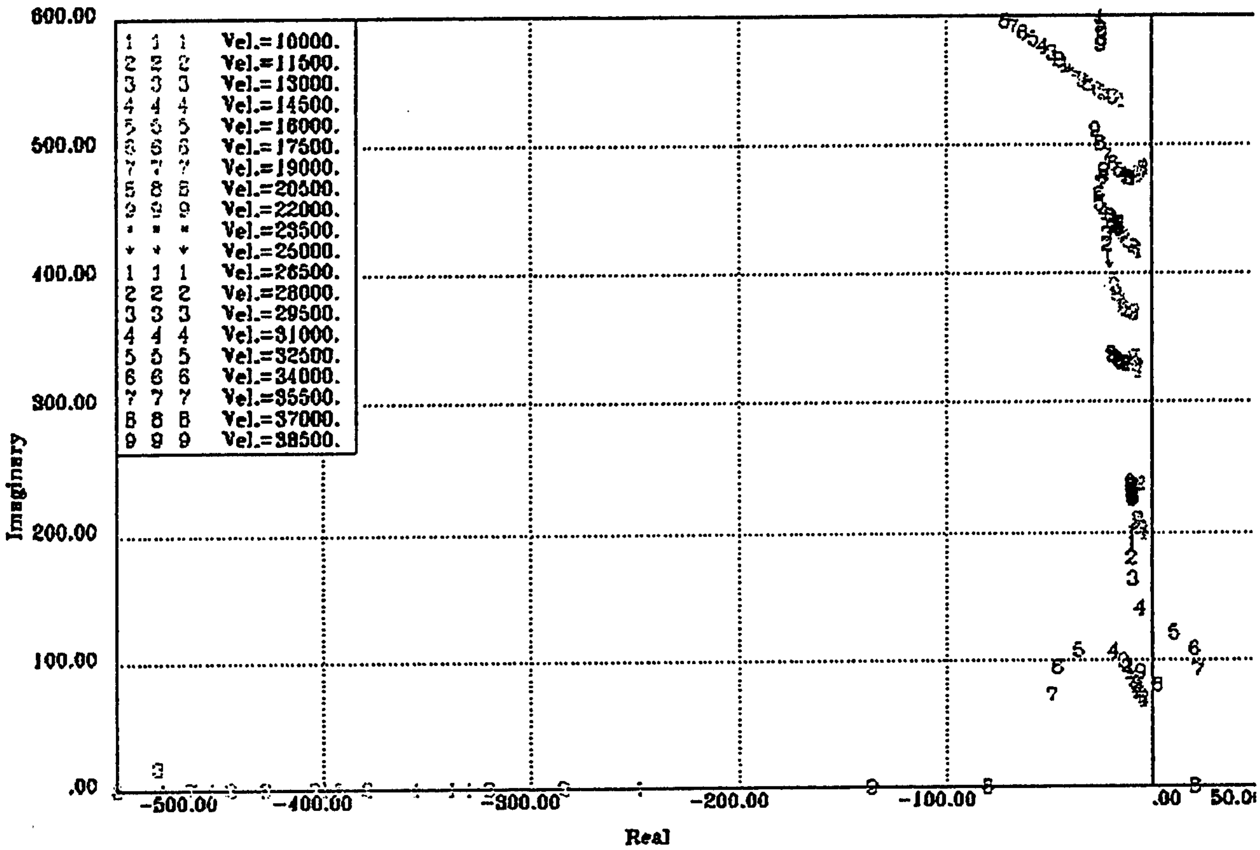


Figure 4.1.21 **Root-Locus Plot of GAF Model: M = 3.0, by ZONA7U of ASTROS***
(Flutter Speed = 31,536 *in/sec*, Flutter Frequency = 21.3 *Hz*).

4.2 Case 1.b: GAF (Generalized Advanced Fighter) Wing Model Optimization

- *Purpose:* To test a public domain model in static, normal modes, and flutter optimization and MDO.

- *Description of input and results:*

4.2.1 Static Optimization

Static structural design optimization was performed. The design variables were the thicknesses of all skin elements. The objective function was the total weight of the skins. The constraints were the requirements for wing tip displacement and the stresses in the skins. The required wing tip displacement, 27.07 *in*, was the same as the result in the analysis of the original wing model. The required stress of 64,000 *psi* was the maximum stress in the same analysis. The number of global design variables was 52, and the design variables and their numbering are shown in Fig 4.2.1. The design variables were defined by **DESVARP** cards, which converted the properties of the elements into design variables. The upper and lower skins had the same property numbers and, thus, were the same design variables. This had the effect of linking the design variables of the upper and lower skins. The lower boundary of the design variables was the minimum material size, 0.118 *in*.

As a result of the static design optimization, the weight was reduced from 343.49 *lbs* to 313.37 *lbs*. In this optimization, the thicknesses of all skins started from their minimum basic material sizes. The iteration history of the design optimization is shown in Fig 4.2.2 and Table 4.2.1. The required CPU time was 1 minute 55.5 seconds. An 8.8 % weight reduction was achieved for this short CPU time in 15 iterations. The convergence was excellent.

4.2.2 Normal Modes Optimization

In the normal modes optimization, the lower bound of the first frequency was used as a constraint. The required frequency of 10.22 *Hz* was the same as the result from the original analysis of the model.

As a result of the normal modes design optimization, the weight was reduced from the original weight of 343.49 *lbs* to 312.26 *lbs*. The iteration history of the design optimization is also shown in Fig 4.2.2 and in Table 4.2.2. The required CPU time was 2 minute 48.3 seconds. A 9.1 % weight reduction was achieved for this short CPU time in 15 iterations. The convergence was excellent for this case with a structural design optimization and only one constraint.

4.2.3 Design Optimization for Static Loads and Normal Modes

Design optimization for static loads and normal modes was then performed. Displacements, stresses, and the lowest frequency were used as constraints. The constraint values, the required wing tip displacement of 27.07 *in*, the required maximum stress of 64,000 *psi*, and the required lowest frequency of 10.22 *Hz*, were the same as resulted from the original analyses.

As a result of the design optimization for the disciplines of statics and normal modes, the weight was reduced from 343.49 *lbs*, the weight of the original structure, to 313.28 *lbs*, for a reduction of about 10 %. More weight could still be taken off for smaller minimum basic sizes. The iteration history of the design optimization is again shown in Fig 4.2.2 and in Table 4.2.3. The final design variable values are given in Table 4.2.4. In this optimization, the initial design variable values were the minimum basic sizes not those from the original structure. This means that the design optimization can be performed easily without any initial sizing calculations either manually or by CAD.

4.2.4 Flutter Optimization

Structural design optimization with a flutter speed constraint was performed for the GAF model at M=0.85. ZONA6 in ASTROS* was used for calculating the aerodynamic loads. The constrained flutter speed was 16,107.8 *in/sec.* Flutter sensitivities with respect to design variables were calculated, the flutter constraints were formulated by linear approximation, and the optimization problem was solved using the optimizer NPSOL. The derivatives of the mass matrix and the stiffness matrix, necessary to calculate the flutter sensitivities, were obtained using the *MAPOL* language in ASTROS* for the static and normal modes disciplines. An iteration history of the design optimization for flutter speed is shown in Fig 4.2.3 and in Table 4.2.5. In this case, the lengthy set of iterations was stopped without applying the convergence criteria since the intent was only to show the convergence behavior.

4.2.5 Multidisciplinary Design Optimization of Statics, Normal Modes, and Flutter

With flutter speed, static strength, and frequency constraints, multidisciplinary design optimization was performed for the GAF model. The objective function was the total structural weight. The approximate optimization problem was calculated by NPSOL. The sensitivities of the static strength and frequency constraints, as well as the derivatives of the mass and stiffness matrices that are necessary to calculate the flutter sensitivities were obtained via the *MAPOL* programming language in ASTROS* from the static and normal modes disciplines. The sensitivity of the objective function, the total structural weight, was also obtained via *MAPOL.* The constraint values were the required wing tip displacement of 27.07 *in*, the required maximum stress of 64,000 *psi*, the required lowest frequency of 10.22*Hz*, and the required flutter speed of 16,108 *in/sec*. An iteration history of the multidisciplinary optimization with strength, displacement, natural frequency, and flutter speed constraints is shown in Fig 4.2.4 and Table 4.2.6. The final design variable values are given in Table 4.2.7. A weight reduction of 15.57 *lbs* was achieved compared with the weight of the original model, 343.49 *lbs*; this was a 4.5 % weight reduction in 6 iterations. The GAF model was an actual aircraft wing model supposed to be well designed at the outset, and the material minimum basic sizes were quite thick. Thus, a 4.5 % weight reduction in this small number of iterations can be considered a good result since strength, displacement, normal modes, and flutter constraints were considered simultaneously.

Table 4.2.1: Design Iteration History of GAF Model: Structural Optimization for Static Loads.

Iteration Number	Objective Function	Function Evaluation	Gradient Evaluation	Retained Constraints	Active Constraints	Approximate Convergence
1	2.19373E+02	(Initial Function Value)				
2	2.86841E+02	90	21	45	27	not Converged
3	3.50363E+02	100	8	32	14	not Converged
4	3.40345E+02	36	11	18	6	not Converged
5	3.35738E+02	21	4	16	16	not Converged
6	3.32504E+02	41	3	18	17	not Converged
7	3.21375E+02	22	7	16	4	not Converged
8	3.18522E+02	22	7	17	10	not Converged
9	3.17345E+02	25	3	20	4	not Converged
10	3.16361E+02	23	3	20	4	not Converged
11	3.15494E+02	18	2	17	3	not Converged
12	3.14714E+02	18	3	18	3	not Converged
13	3.14138E+02	19	3	19	3	not Converged
14	3.13609E+02	20	3	19	6	not Converged
15	3.13368E+02	14	2	19	3	Converged

The Final Objective Function Value is: Fixed = 3.28112E+02
+ Designed = 3.13368E+02
Total = 6.41480E+02

Table 4.2.2 Design Iteration History of GAF Model: Structural Optimization for Normal Modes by ASTROS*.

Iteration Number	Objective Function	Function Evaluation	Gradient Evaluation	Retained Constraints	Active Constraints	Approximate Convergence
1	2.19373E+02	(Initial Function Value)				
2	2.71428E+02	90	21	1	1	not Converged
3	3.30081E+02	93	21	1	1	not Converged
4	3.50735E+02	88	7	1	1	not Converged
5	3.35437E+02	31	6	1	1	not Converged
6	3.26556E+02	23	5	1	1	not Converged
7	3.21226E+02	23	5	1	1	not Converged
8	3.18468E+02	24	5	1	1	not Converged
10	3.15728E+02	37	3	1	1	not Converged
11	3.14820E+02	22	4	1	1	not Converged
12	3.13932E+02	22	4	1	1	not Converged
13	3.13314E+02	18	3	1	1	not Converged
14	3.12698E+02	22	4	1	1	not Converged
15	3.12255E+02	26	2	1	1	Converged

The Final Objective Function Value is: Fixed = 3.28112E+02
+ Designed = 3.12255E+02
Total = 6.40367E+02

Table 4.2.3 Design Iteration History of GAF Model:
Structural Optimization for Statics and Normal Modes by ASTROS*.

Iteration Number	Objective Function	Function Evaluation	Gradient Evaluation	Retained Constraints	Active Constraints	Approximate Convergence
1	2.19373E+02 (Initial Function Value)					
2	2.96459E+02	N/A FSD	N/A FSD	163	N/A FSD	not Converged
3	3.06451E+02	N/A FSD	N/A FSD	163	N/A FSD	not Converged
4	3.04878E+02	N/A FSD	N/A FSD	163	N/A FSD	not Converged
8	3.16221E+02	15	4	35	3	not Converged
9	3.15302E+02	18	3	35	3	not Converged
10	3.14613E+02	18	3	34	3	not Converged
11	3.14112E+02	10	3	34	4	not Converged
12	3.13653E+02	30	2	34	13	not Converged
13	3.13341E+02	16	2	34	3	not Converged
14	3.13282E+02	14	2	36	3	Converged

The Final Objective Function Value is: Fixed = 3.28112E+02
+ Designed = 3.13282E+02
Total = 6.41394E+02

Table 4.2.4 Final Design Variables of GAF Model:
Structural Optimization for Statics and Normal Modes by ASTROS*.

Design Variable	Design Value	Minimum Value	Maximum Value	Objective Sensitivity
102	1.00000E+00	1.00000E+00	2.63158E+01	6.17620D+01
501	1.00000E+00	1.00000E+00	1.00000E+01	2.40229D+00
502	1.00000E+00	1.00000E+00	1.00000E+01	2.37495D+00
503	6.32244E+00	1.00000E+00	1.00000E+01	2.39868D+00
504	1.00000E+00	1.00000E+00	1.00000E+01	2.79464D+00
505	1.00000E+00	1.00000E+00	1.00000E+01	1.80651D+00
506	1.00000E+00	1.00000E+00	1.00000E+01	4.44667D+00
507	1.00000E+00	1.00000E+00	1.00000E+01	4.39610D+00
508	5.62066E+00	1.00000E+00	1.00000E+01	4.43999D+00
509	1.00000E+00	1.00000E+00	1.00000E+01	5.17293D+00
510	1.00000E+00	1.00000E+00	1.00000E+01	3.34383D+00
511	1.00000E+00	1.00000E+00	1.00000E+01	3.96945D+00
512	1.00000E+00	1.00000E+00	1.00000E+01	3.92430D+00
513	4.27849E+00	1.00000E+00	1.00000E+01	3.96349D+00
514	1.00000E+00	1.00000E+00	1.00000E+01	4.61772D+00
515	1.00000E+00	1.00000E+00	1.00000E+01	2.98490D+00

516	1.00000E+00	1.00000E+00	1.00000E+01	3.49222D+00
517	1.11060E+00	1.00000E+00	1.00000E+01	3.45248D+00
518	2.29648E+00	1.00000E+00	1.00000E+01	3.48694D+00
519	1.00000E+00	1.00000E+00	1.00000E+01	8.12499D+00
520	1.00000E+00	1.00000E+00	1.00000E+01	2.62597D+00
521	1.00000E+00	1.00000E+00	1.00000E+01	3.01498D+00
522	1.11721E+00	1.00000E+00	1.00000E+01	2.98071D+00
523	1.43451E+00	1.00000E+00	1.00000E+01	3.01046D+00
524	1.00000E+00	1.00000E+00	1.00000E+01	7.01463D+00
525	1.00000E+00	1.00000E+00	1.00000E+01	2.26705D+00
526	1.00000E+00	1.00000E+00	1.00000E+01	2.53777D+00
527	1.00000E+00	1.00000E+00	1.00000E+01	2.50890D+00
528	1.00000E+00	1.00000E+00	1.00000E+01	2.53393D+00
529	1.00000E+00	1.00000E+00	1.00000E+01	5.90423D+00
530	1.00000E+00	1.00000E+00	1.00000E+01	1.90813D+00
531	1.00000E+00	1.00000E+00	1.00000E+01	2.06054D+00
532	1.00000E+00	1.00000E+00	1.00000E+01	2.03709D+00
533	1.00000E+00	1.00000E+00	1.00000E+01	2.05740D+00
534	1.00000E+00	1.00000E+00	1.00000E+01	4.79383D+00
535	1.00000E+00	1.00000E+00	1.00000E+01	1.54923D+00
536	1.00000E+00	1.00000E+00	1.00000E+01	1.58330D+00
537	1.00000E+00	1.00000E+00	1.00000E+01	1.56532D+00
538	1.00000E+00	1.00000E+00	1.00000E+01	1.58091D+00
539	1.00000E+00	1.00000E+00	1.00000E+01	3.68346D+00
540	1.00000E+00	1.00000E+00	1.00000E+01	1.19032D+00
541	1.00000E+00	1.00000E+00	1.00000E+01	6.12696D-01
542	1.00000E+00	1.00000E+00	1.00000E+01	6.05731D-01
543	1.00000E+00	1.00000E+00	1.00000E+01	6.11756D-01
544	1.00000E+00	1.00000E+00	1.00000E+01	1.42533D+00
545	1.00000E+00	1.00000E+00	1.00000E+01	4.60569D-01

Table 4.2.5 Design Iteration History of GAF Model:
Structural Optimization with Flutter Constraint at $M = 0.85$.

Iteration No.	Weight (*lbs*)	Flutter Speed (*in/sec*)	Flutter Frequeny (*rad/sec*)
1	343.78	16107.9 (Constraint)	105.74
2	324.12	16029.3	103.21
3	348.26	16200.6	103.85
4	315.77	15979.9	102.46
5	339.22	16158.3	103.13
6	315.77	15979.0	102.46
7	327.59	16076.0	102.86
8	339.76	16162.0	103.03
9	327.47	16077.4	102.78
10	333.61	16121.0	102.90
11	328.68	16085.8	102.82
12	333.15	16104.1	102.85

Table 4.2.6 Design Iteration History of GAF Model:
Multidisciplinary Design Optimization at $M = 0.85$
(Stress + Displacement + Natural Frequency +Flutter Speed).

Iteration No.	Weight (*lbs*)	F. Speed (*in/sec*)	F.freq. (*Hz*)	Tip Disp. (*in*)	M. Stress (*psi*)	1^{st} Freq. (*Hz*)
Required		16,107.8		27.38	64,000	10.208
1	219.37	15,232.2	13.72	63.38	164,000	6.00
2	324.61	16,086.6	14.38	37.20	125,000	8.07
3	386.50	16,517.5	14.42	25.57	76,260	9.32
4	366.36	16,492.7	16.42	25.29	64,260	10.28
5	339.64	16,267.7	16.60	26.44	62,550	10.32
6	328.86	16,112.3	16.45	26.44	62,480	10.32
7	327.92	16,106.2	16.44	26.80	63,650	10.27

Table 4.2.7 Final Design Variable Values of GAF Model: Multidisciplinary Design Optimization at $M = 0.85$ (Stress + Displacement + Natural Frequency +Flutter Speed).

Variable	State	Value	L. bound	U. bound	Lagr multip.
VARBL 1	LL	1.0000	1.0000	1.0100	61.60661
VARBL 2	LL	1.3210	1.3210	1.3476	2.417356
VARBL 3	LL	3.0350	3.0350	3.0960	2.413862
VARBL 4	LL	5.0275	5.0275	5.1286	2.405284
VARBL 5	LL	1.0000	1.0000	1.0100	2.803832
VARBL 6	LL	1.0000	1.0000	1.0100	1.755699
VARBL 7	LL	1.3176	1.3176	1.3441	4.126373
VARBL 8	LL	2.8860	2.8860	2.9441	4.255834
VARBL 9	LL	4.3147	4.3147	4.4014	4.670451
VARBL 10	LL	1.0000	1.0000	1.0100	5.299779
VARBL 11	LL	1.0000	1.0000	1.0100	3.263696
VARBL 12	LL	1.1785	1.1785	1.2022	3.411701
VARBL 13	LL	2.1322	2.1322	2.1751	2.354970
VARBL 14	FR	3.4188	3.4037	3.4721	.000000
VARBL 15	LL	1.0000	1.0000	1.0100	4.830757
VARBL 16	LL	1.0000	1.0000	1.0100	2.668114
VARBL 17	LL	1.3602	1.3602	1.3876	2.827459
VARBL 18	LL	1.7225	1.7225	1.7571	2.866750
VARBL 19	LL	1.6573	1.6573	1.6906	3.743286
VARBL 20	LL	1.0000	1.0000	1.0100	8.890014
VARBL 21	LL	1.0000	1.0000	1.0100	2.52555
VARBL 22	LL	1.1280	1.1280	1.1507	2.982377
VARBL 23	LL	1.3032	1.3032	1.3294	3.038492
VARBL 24	LL	1.2682	1.2682	1.2937	3.038216
VARBL 25	LL	1.0000	1.0000	1.0100	7.012024
VARBL 26	LL	1.0000	1.0000	1.0100	2.286383
VARBL 27	LL	1.0000	1.0000	1.0100	2.525305
VARBL 28	LL	1.0221	1.0221	1.0427	2.497412
VARBL 29	LL	1.0000	1.0000	1.0100	2.541466
VARBL 30	LL	1.0000	1.0000	1.0100	5.922578
VARBL 31	LL	1.0000	1.0000	1.0100	1.907490
VARBL 32	LL	1.0000	1.0000	1.0100	2.060489
VARBL 33	LL	1.0000	1.0000	1.0100	2.033227
VARBL 34	LL	1.0000	1.0000	1.0100	2.053379
VARBL 35	LL	1.0000	1.0000	1.0100	4.786958
VARBL 36	LL	1.0000	1.0000	1.0100	1.548409
VARBL 37	LL	1.0000	1.0000	1.0100	1.582935
VARBL 38	LL	1.0000	1.0000	1.0100	1.565027
VARBL 39	LL	1.0000	1.0000	1.0100	1.580414
VARBL 40	LL	1.0000	1.0000	1.0100	3.682065
VARBL 41	LL	1.0000	1.0000	1.0100	1.189650

VARBL 42	LL	1.0000	1.0000	1.0100	.611605
VARBL 43	LL	1.0000	1.0000	1.0100	.605568
VARBL 44	LL	1.0000	1.0000	1.0100	.611541
VARBL 45	LL	1.0000	1.0000	1.0100	1.424990
VARBL 46	LL	1.0000	1.0000	1.0100	.460554
VARBL 47	LL	1.4474	1.4474	1.4765	4.104928
VARBL 48	LL	2.8321	2.8321	2.8890	4.009018
VARBL 49	LL	4.4457	4.4457	4.5350	3.914433
VARBL 50	LL	1.3709	1.3709	1.3985	4.135922
VARBL 51	LL	2.8615	2.8615	2.9190	3.974858
VARBL 52	LL	4.3594	4.3594	4.4470	3.893831

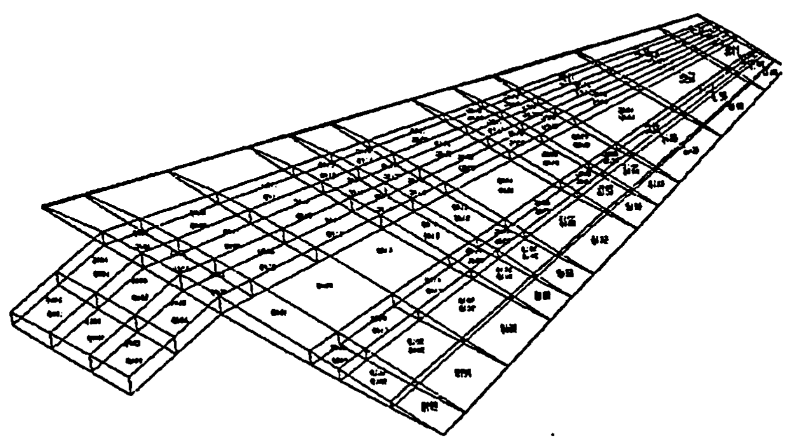


Figure 4.2.1 Design Variables and Numbering of GAF Model.

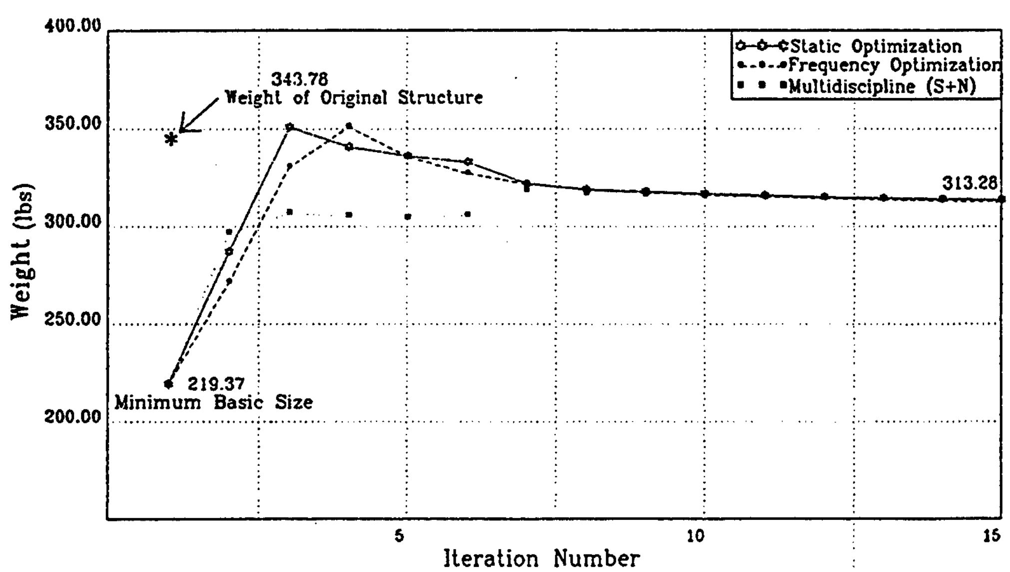


Figure 4.2.2 **Iteration History of Structural Design Optimization of GAF Model: Statics, Normal Modes, and Both Disciplines (S + N) by ASTROS*.**

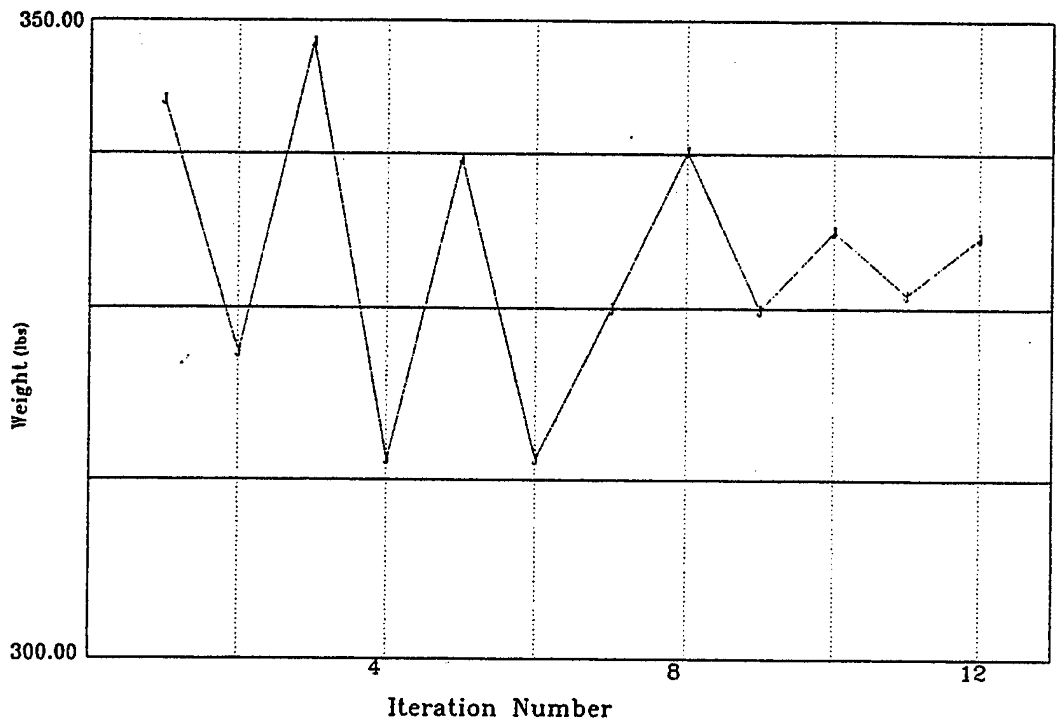


Figure 4.2.3 **Iteration History of Structural Design Optimization of GAF Model: Flutter Discipline at M = 0.85, by Root-Locus Method.**

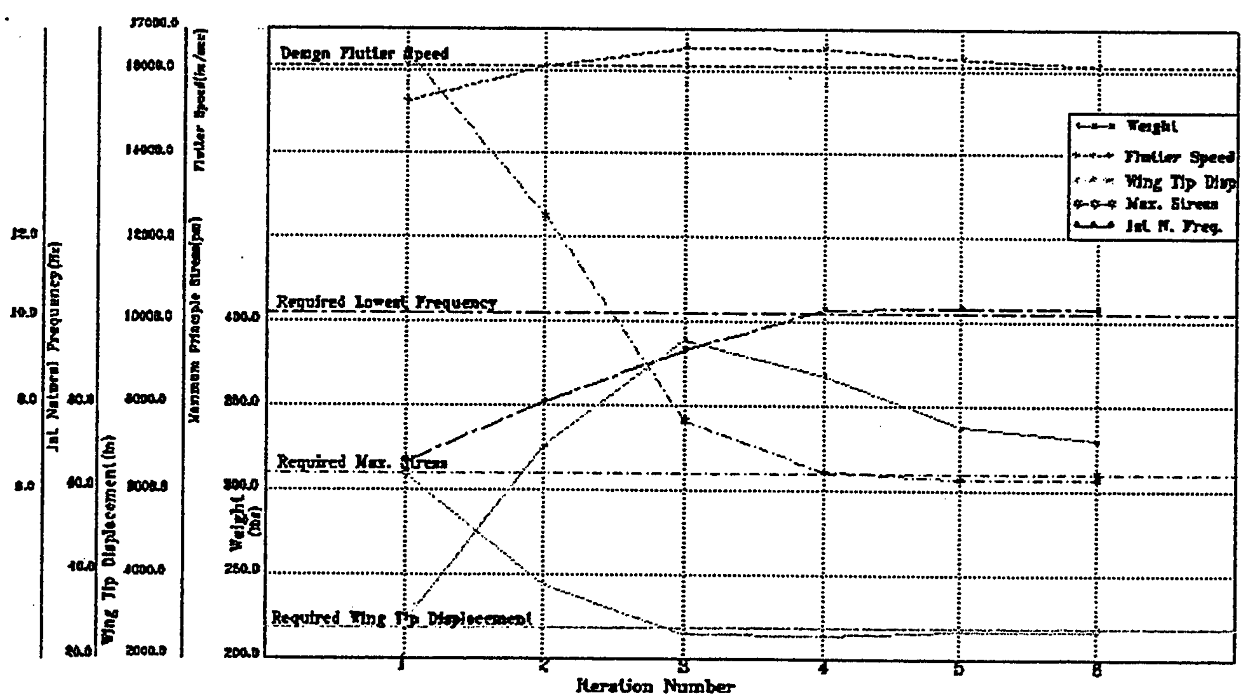


Figure 4.2.4 **Design Iteration History of GAF Model: Multidisciplinary Design Optimization (Constraints on stress, displacement, natural frequency, flutter speed).**

4.3 Case 2.a: DAST (Drones for Aerodynamic and Structural Testing) Wing Model Analysis

- *Purpose:* To test a composite structural wing model in static aeroelastic, normal modes, and flutter analysis.

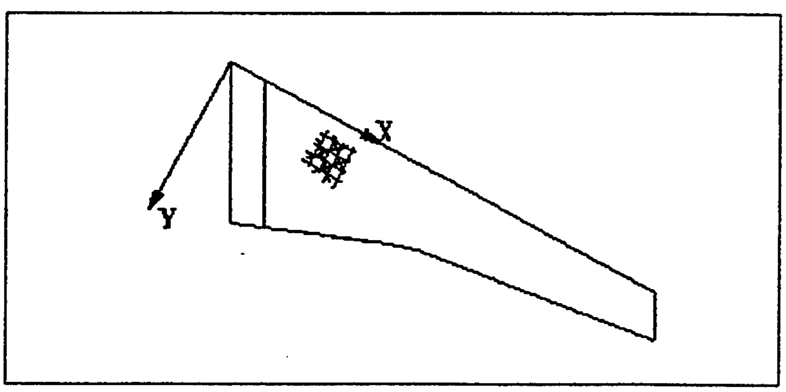
- *Description of input and results:*

The DAST wing model was a structural model of a supercritical wing used on a drone in a flight test facility. The ASTROS* and MSC/NASTRAN data for the DAST model were obtained by converting data from an EAL (Engineering Analysis Language) model. The DAST model was a skin-spar-rib type wing made of composite material. To avoid an excessive number of local modes in the normal modes analysis and to improve performance of the model in the static aeroelastic and flutter analyses, ribs were added to the original structure. The stacking sequence of the composite skin panels was changed from the original stacking sequence [90/0] to a more realistic [90/±45/0].

Analyses and structural design optimizations of a composite wing model were the specific goal here. The boundary condition of the structure was free at the root, and its behavior was thought to be the same as that of a full aircraft. More details about the model, the test cases, and their application to this model are given in Appendix A.

4.3.1 Structural Configuration and Static Aeroelastic Analysis

A fuselage weight of 1177.2 *lbs* was added to the wing root by a **CONM2** entry, and the total weight of the model became 1250.0 *lbs*, half the weight of the DAST model. The wing had two trailing edge control surfaces. Steady flight in the trim condition with control surface deflections was assumed. The skins were modeled by plate elements, composed of four plies. The material coordinates are shown in the following:



The lamina material of the composite was assumed to be AS/3501 graphite/epoxy. The stiffness and strength of each lamina are given below:

Lamina Stiffness:
$E_1 = 1.8 \times 10^6$ (*psi*)
$E_2 = 0.86 \times 10^6$ (*psi*)
$\upsilon_{12} = 0.3$
$G_{12} = G_{1z} = G_{2z} = 0.46 \times 10^6$ (*psi*)
$\rho = 0.057$ (*lbs/in*^{3})

Lamina Strength:
$S_L^{(+)} = 210{,}000$ (*psi*)
$S_L^{(-)} = 170{,}000$ (*psi*)
$S_T^{(+)} = 7{,}000$ (*psi*)
$S_T^{(-)} = 36{,}000$ (*psi*)
$S_{LT} = 9{,}000$ (*psi*)

The skins were modeled by **CQUAD4** and **CTRIA3** elements and the spar caps by **CBAR** elements. The property cards for the **CQUAD4** and **CTRIA3** elements were **PCOMP** entries. The structural configuration of the FEM model is shown in Fig 4.3.1. A summary of the number of grid points and elements is shown in the following.

NUMBER OF GRID POINTS	428
NUMBER OF ELEMENTS	1680
CROD	432
CONM2	449
CCBAR	172
CQUAD4	623
CTRIA3	4

Two **CAERO7** cards were used to generate the aerodynamic boxes because the trailing edge consisted of two separate straight lines. The inboard wing was composed of 15 x 7 boxes and the outboard wing of 15 x 10 boxes, thus, the total number of boxes was 275.

Symmetric static aeroelastic analysis was performed and the trim parameters, angle-of-attack and control surface deflection angle, were calculated under a 10g pull-up condition with zero pitching rate and zero pitching acceleration at Mach M=0.80. The inboard control surface was assumed to be fixed. The trim parameters were calculated when the structure was rigid and when the structure had elastic deformation. The displacements at given **GRID** points and the stresses in each ply of the plate elements were calculated at this trim condition. ZONA6 was used to calculate the aerodynamics.

The weight data output is shown in Table 4.3.1 including the fuselage weight. The longitudinal stability derivatives of the aircraft for both the rigid and elastic cases are shown in Table 4.3.2. The calculated trim parameters for both the rigid and flexible structure at the trim condition are given in Table 4.3.3. The calculated angle-of-attack, 4.06° for the rigid case, was reasonable and a large deflection angle, -45.98°, of the control surface was necessary to obtain trim since no horizontal tail was included. The steady pressure distributions as attributed to each parameter such as thickness, camber, angle-of-attack, pitching rate, pitching acceleration, and control surface deflection are shown in Table 4.3.4. The steady pressure distributions in the trim condition for all trim parameters are shown in Fig 4.3.2. The vertical displacement at **GRID** point 415 on the wing tip was 5.506 *in*, and the deflection shape in the trim condition is presented in Fig 4.3.3. This value was later used as constraint in the structural design optimization. The required CPU time was 9 minutes 25.0 seconds.

4.3.2 Aerodynamic Configuration and Analysis by ENSAERO

The aerodynamic analysis of the wing was performed by the CFD code, ENSAERO. The aerodynamic configuration of the wing is shown in Fig 4.3.4. The input data for this model were very similar to those for the GAF model. Steady aerodynamic pressure coefficients were calculated for Navier-Stokes flow. For all cases, the Reynolds number was 10,000,000, and spanwise and normal viscous terms were used. For turbulence, the Baldwin-Lomax turbulence model was used and, for correction for vortex flow, Degani-Schiff modeling. The iteration indices were less than 1.0E-09, and there were about 500 iterations for Euler flow and then another 500+ iterations for Navier-Stokes flow. The total size of the grid was 151 x 44 x 34 in the x-, y-, and z- directions, respectively. The number of grid points on the wing was 61 x 34 on both the lower and upper surfaces. The results of the calculated aerodynamic pressure coefficients for Navier Stokes flow are shown in Fig 4.3.5 for four cases:

(1) $M = 0.70$, $\alpha = 0.0°$, (Navier-Stokes Flow)
(2) $M = 0.70$, $\alpha = 5.0°$, (Navier-Stokes Flow)
(3) $M = 0.80$, $\alpha = 0.0°$, (Euler Flow)
(4) $M = 0.80$, $\alpha = 0.0°$, (Navier-Stokes Flow)

Fig 4.3.5 shows that the DAST model was just entering the transonic regime at Mach M = 0.7 when the angle-of-attack was 0.0° and was in the transonic regime at Mach 0.8. The strength of the shock in Euler flow was larger than that in Navier-Stokes flow.

4.3.3 Normal Modes Analysis Using ASTROS*

Natural frequencies, the associated modes shapes, and the generalized stiffness and mass matrices were calculated in the normal modes discipline as for the GAF model. To calculate eigenvalues, the INV (Inverse Power) method was used. Normal modes data for 10 modes from the lowest to 200.0 *Hz* were calculated for a symmetric boundary condition. The axial direction of the fuselage was fixed. The first two modes were the rigid body modes, vertical translation and pitching rotation. The lowest seven natural frequencies of the elastic modes were 11.3, 48.7, 55.7, 103.3, 130.8, 147.8, and 199.0 *Hz*. The required CPU time was 2 minutes 11.0 seconds.

The results of the computations are shown in Table 4.3.5, and the mode shapes are plotted in Fig 4.3.6. These data were later used in the flutter analysis. The lowest natural frequency, 10.22 *Hz*, was used as a constraint in the normal modes design optimization.

4.3.4 Flutter Analysis

Flutter analyses were performed by the K-method in ASTROS* and by the root-locus method for a Mach number of $M = 0.80$ using ZONA6 and ZTAIC methods. The results from ASTROS* and the root-locus method were compared and are shown in Table 4.3.6. The generalized unsteady aerodynamic loads calculated in ASTROS* were used in the root-locus method.

These generalized unsteady aerodynamic loads at $M = 0.85$ calculated by ZONA6 in ASTROS* and are shown in Fig 4.3.7. The generalized unsteady aerodynamic loads calculated by ZONA6 and approximated by the minimum-state method at $M = 0.85$ are presented in Fig 4.3.8. The V-f and V-g plots for the flutter results by ZONA6 in ASTROS* are shown in Fig 4.3.9 and the root-locus plots to calculate the flutter speed using the aerodynamics of ZONA6 in ASTROS* are given in Figs 4.3.10. The V-f and V-g plots for the flutter results by ZTAIC in ASTROS* are shown in Fig 4.3.11, and the root-locus plots to calculate the flutter speed using the aerodynamics of ZTAIC in ASTROS* are given in Figs 4.3.12. The flutter speed and flutter frequency by the K-method and ZONA6 were 14,358 *in/sec* and 48.67 *Hz*, respectively. The flutter speed and flutter frequency by the root-locus method and ZONA6 were 13,490 *in/sec* and 36.3 *Hz*, respectively. The flutter speed and flutter frequency by the K-method and ZTAIC were 11,800 *in/sec* and 56.01 *Hz*, respectively. Finally, the flutter speed and flutter frequency by the root-locus method and ZTAIC were 12,892 in/sec and 49.30 *Hz*, respectively. The required CPU time by the K-method and ZONA6 of ASTROS* was 13 minutes 13.5 seconds and that by the K-method and ZTAIC of ASTROS* 5 hours 22 minutes 31.4 seconds, respectively.

Table 4.3.1 Weight Data Output of DAST Model.

OUTPUT FROM GRID POINT WEIGHT GENERATOR

REFERENCE POINT = 1

XO = 2.417731E+02, YO = 1.805970E+01, ZO = 5.992480E+01

M O

*	1.3002E+03	0.0000E+00	0.0000E+00	0.0000E+00	-1.258E+03	6.7508E+03	*
*	0.0000E+00	1.3002E+03	0.0000E+00	1.2586E+03	0.000E+00	2.6715E+04	*
*	0.0000E+00	0.0000E+00	1.3002E+03	-6.7508E+03	-2.671E+04	0.0000E+00	*
*	0.0000E+00	1.2586E+03	-6.7508E+03	3.3057E+05	5.025E+04	2.8499E+04	*
*	-1.2586E+03	0.0000E+00	-2.6715E+04	5.0253E+04	8.815E+05	1.1363E+03	*
*	6.7508E+03	2.6715E+04	0.0000E+00	2.8499E+04	1.136E+03	1.1457E+06	*

AXIS SYSTEM (S)	MASS	DIRECTION X-C.G.	Y-C.G.	Z-C.G.
X	1.300231E+03	0.000000E+00	-5.192037E+00	-9.680215E-01
Y	1.300231E+03	2.054661E+01	0.000000E+00	-9.680215E-01
Z	1.300231E+03	2.054661E+01	-5.192037E+00	0.000000E+00

I(Q)

*	5.62043E+05			*
*		2.22358E+05		*
*			4.03149E+05	*

Table 4.3.2 Non-Dimensional Longitudinal Stability Derivatives of DAST Model: 10*g* Pull-up Maneuver, $M = 0.8$, by ZONA6 of ASTROS* for Rigid and Flexible Structure.

TRIM IDENTIFICATION = 1 REFERENCE GRID = 446

REFERENCE AREA = 2.8236E+03 REFERENCE CHORD = 4.0000E+01

	<< LIFT >>			<< PITCHING MOMENT >>		
PARAMETER	RIGID DIRECT	RIGID SPLINED	FLEX.	RIGID DIRECT	RIGID SPLINED	FLEXIBLE
Thickness/Camber	0.9860	0.9876	0.9097	-0.5291	-0.5291	-0.4653
Angle of Attack (1/*deg*)	0.2222	0.2224	0.2193	-0.0821	-0.0822	-0.0751
Angle of Attack (1/*rad*)	12.7330	12.7418	12.5669	-4.7045	-4.7117	-4.3015
Pitch Rate (s/*deg*)	0.3004	0.3007	0.2889	-0.1578	-0.1579	-0.1427
Pitch Rate (s/*rad*)	17.2142	17.2293	16.5505	-9.0398	-9.0457	-8.1754
Control Surface 1 (1/*deg*)	0.0255	0.0255	0.0241	-0.0119	-0.0119	-0.0110
Control Surface 1 (1/*rad*)	1.4584	1.4597	1.3820	-0.6799	-0.6804	-0.6292
Control Surface 2 (1/*deg*)	0.0105	0.0105	0.0086	-0.0104	-0.0104	-0.0085
Control Surface 2 (1/*rad*)	0.6039	0.6039	0.4951	-0.5945	-0.5945	-0.4863

Table 4.3.3 Trim Parameters of DAST Model:
10*g* Pull-up Maneuver, *M* = 0.80, by ZONA6 of ASTROS* for Rigid and Flexible Structure.

TRIM RESULTS FOR TRIM SET 1 OF TYPE PITCH
MACH NUMBER 8.00000E-01
DYNAMIC PRESSURE 6.55000E+00
VELOCITY 1.02700E+04
TRIM PARAMETERS:

DEFINITION	LABEL	FLEXIBLE	RIGID		
LOAD FACTOR	"NZ"	3.86399E+03	3.86399E+03		(Input)
PITCH ACCELERATION	"QACCEL"	0.00000E+00	0.00000E+00	*rad/s*^{2}	(Input)
ANGLE OF ATTACK	"ALPHA"	4.03914E+00	4.06115E+00	*deg*	(Computed)
CONTROL SURFACE	"AIL1"	0.00000E+00	0.00000E+00	*deg*	(Input)
CONTROL SURFACE	"AIL2"	-4.50767E+01	-4.59823E+01	*deg*	(Computed)
PITCH RATE	"QRATE"	0.00000E+00	0.00000E+00	*deg/s*	(Input)
THICKNESS/CAMBER	"THKCAM"	1.00000E+00	1.00000E+00		(Input)

Table 4.3.4 Pressure Distribution of DAST Model:
10*g* Pull-up Maneuver, *M* = 0.80, by ZONA6 of ASTROS*, for Rigid Structure.

***** STEADY RIGID AERODYNAMIC PRESSURE OF TRIM PARAMETERS, MACH = 0.8

	NZ /	QACCEL /	THKCAM /	ALPHA /	QRATE /	AIL1 /	AIL2 /
EXT ID	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
100001	0.000E+00	0.0000E+00	0.1187E+01	0.3902E+00	0.1944E+02	0.1130E-01	0.1297E-02
100002	0.000E+00	0.0000E+00	0.3618E-02	0.1648E+00	0.5510E+02	0.5688E-02	0.6083E-03
100003	0.000E+00	0.0000E+00	0.3257E+00	0.1358E+00	0.7387E+02	0.5331E-02	0.5410E-03
100004	0.000E+00	0.0000E+00	0.3145E+00	0.1146E+00	0.8996E+02	0.5203E-02	0.4977E-03
100005	0.000E+00	0.0000E+00	0.2030E+00	0.9709E-01	0.1070E+03	0.5334E-02	0.4711E-03
100006	0.000E+00	0.0000E+00	0.1223E+00	0.8566E-01	0.1186E+03	0.5604E-02	0.4587E-03
100007	0.000E+00	0.0000E+00	0.1675E+00	0.7631E-01	0.1269E+03	0.5946E-02	0.4493E-03
100008	0.000E+00	0.0000E+00	0.2747E+00	0.6763E-01	0.1321E+03	0.6348E-02	0.4390E-03
100010	0.000E+00	0.0000E+00	0.3706E+00	0.5213E-01	0.1314E+03	0.7075E-02	0.4055E-03
100011	0.000E+00	0.0000E+00	0.5720E+00	0.4458E-01	0.1249E+03	0.7226E-02	0.3770E-03
100012	0.000E+00	0.0000E+00	0.7607E+00	0.3684E-01	0.1134E+03	0.7027E-02	0.3366E-03
100013	0.000E+00	0.0000E+00	0.8239E+00	0.2910E-01	0.9704E+02	0.6332E-02	0.2843E-03
100014	0.000E+00	0.0000E+00	0.7120E+00	0.2675E-01	0.9062E+02	0.5954E-02	0.2648E-03
100095	0.000E+00	0.0000E+00	0.1553E+00	0.1345E+00	0.1924E+03	0.1359E-01	0.1047E-02
100096	0.000E+00	0.0000E+00	0.3246E+00	0.1135E+00	0.1798E+03	0.1395E-01	0.9832E-03
100097	0.000E+00	0.0000E+00	0.3363E+00	0.9745E-01	0.1695E+03	0.1480E-01	0.9392E-03
100098	0.000E+00	0.0000E+00	0.3187E+00	0.8368E-01	0.1593E+03	0.1623E-01	0.9021E-03
100099	0.000E+00	0.0000E+00	0.3592E+00	0.7209E-01	0.1489E+03	0.1820E-01	0.8664E-03
100100	0.000E+00	0.0000E+00	0.4803E+00	0.6178E-01	0.1373E+03	0.2069E-01	0.8246E-03
100101	0.000E+00	0.0000E+00	0.6898E+00	0.5213E-01	0.1240E+03	0.2341E-01	0.7692E-03
100102	0.000E+00	0.0000E+00	0.9059E+00	0.4272E-01	0.1080E+03	0.2483E-01	0.6926E-03
100103	0.000E+00	0.0000E+00	0.1037E+01	0.3365E-01	0.8960E+02	0.2183E-01	0.5918E-03
100104	0.000E+00	0.0000E+00	0.9455E+00	0.3095E-01	0.8326E+02	0.1956E-01	0.5533E-03
100105	0.000E+00	0.0000E+00	0.4757E+00	0.1950E-01	0.5492E+02	0.1143E-01	0.3741E-03
200001	0.000E+00	0.0000E+00	0.1347E+01	0.6808E+00	0.7119E+03	0.4181E-01	0.4223E-02
200002	0.000E+00	0.0000E+00	0.6021E+00	0.2752E+00	0.3165E+03	0.1890E-01	0.1857E-02
200003	0.000E+00	0.0000E+00	0.4546E+00	0.2171E+00	0.2684E+03	0.1633E-01	0.1574E-02

200004	0.000E+00	0.0000E+00	0.3411E+00	0.1745E+00	0.2343E+03	0.1468E-01	0.1382E-02
200005	0.000E+00	0.0000E+00	0.1682E+00	0.1392E+00	0.2075E+03	0.1374E-01	0.1245E-02
200006	0.000E+00	0.0000E+00	0.3490E+00	0.1173E+00	0.1910E+03	0.1351E-01	0.1175E-02
200007	0.000E+00	0.0000E+00	0.3562E+00	0.1005E+00	0.1777E+03	0.1358E-01	0.1127E-02
200008	0.000E+00	0.0000E+00	0.3296E+00	0.8611E-01	0.1650E+03	0.1378E-01	0.1088E-02
200009	0.000E+00	0.0000E+00	0.3721E+00	0.7399E-01	0.1524E+03	0.1393E-01	0.1049E-02
200010	0.000E+00	0.0000E+00	0.4953E+00	0.6319E-01	0.1392E+03	0.1375E-01	0.1002E-02
200141	0.000E+00	0.0000E+00	0.1783E+00	0.5911E-01	0.1498E+03	0.2110E-02	0.1439E-01
200142	0.000E+00	0.0000E+00	0.1566E+00	0.4419E-01	0.1179E+03	0.1622E-02	0.1467E-01
200143	0.000E+00	0.0000E+00	0.1282E+00	0.3330E-01	0.9427E+02	0.1258E-02	0.1525E-01
200144	0.000E+00	0.0000E+00	0.1625E+00	0.2552E-01	0.7700E+02	0.9911E-03	0.1575E-01
200145	0.000E+00	0.0000E+00	0.2705E+00	0.1968E-01	0.6344E+02	0.7840E-03	0.1564E-01
200146	0.000E+00	0.0000E+00	0.4903E+00	0.1504E-01	0.5200E+02	0.6138E-03	0.1425E-01
200147	0.000E+00	0.0000E+00	0.6968E+00	0.1123E-01	0.4173E+02	0.4692E-03	0.1147E-01
200148	0.000E+00	0.0000E+00	0.8203E+00	0.8135E-02	0.3242E+02	0.3474E-03	0.8347E-02
200149	0.000E+00	0.0000E+00	0.6733E+00	0.7355E-02	0.2975E+02	0.3151E-03	0.7491E-02
200150	0.000E+00	0.0000E+00	0.2064E+00	0.4303E-02	0.1867E+02	0.1880E-03	0.4241E-02

Table 4.3.5 Results of Normal Modes Analysis of DAST Model.

MODE	EXTRACTION ORDER	EIGENVALUE $(rad/sec)^2$	FREQUENCY *(Hz)*	GENERALIZED MASS	GENERALIZED STIFFNESS
1	1	0.00000E+00	0.00000E+00	1.00000E+00	0.00000E+00
2	2	0.00000E+00	0.00000E+00	1.00000E+00	0.00000E+00
3	7	5.03062E+03	1.12884E+01	1.00000E+00	5.03062E+03
4	6	9.34976E+04	4.86654E+01	1.00000E+00	9.34976E+04
5	4	1.22573E+05	5.57209E+01	1.00000E+00	1.22573E+05
6	3	4.21470E+05	1.03325E+02	1.00000E+00	4.21470E+05
7	5	6.75673E+05	1.30824E+02	1.00000E+00	6.75673E+05
8	8	8.62662E+05	1.47822E+02	1.00000E+00	8.62662E+05
9	9	1.56335E+06	1.98998E+02	1.00000E+00	1.56335E+06

Table 4.3.6 Results of Flutter Analyses of DAST Model.

No.	Mach	Method	Flutter Speed *(in/sec)*	Flutter Freq. *(Hz)*	Remarks
1	0.80	k-method (ZONA6)	14,357.3	48.67	
2	0.80	Root-locus (ZOZA6)	13.489.5	36.30	
3	0.80	k-method (ZTAIC)	11,800.0	56.01	
4	0.80	Root–locus (ZTAIC)	12,892.0	49.30	

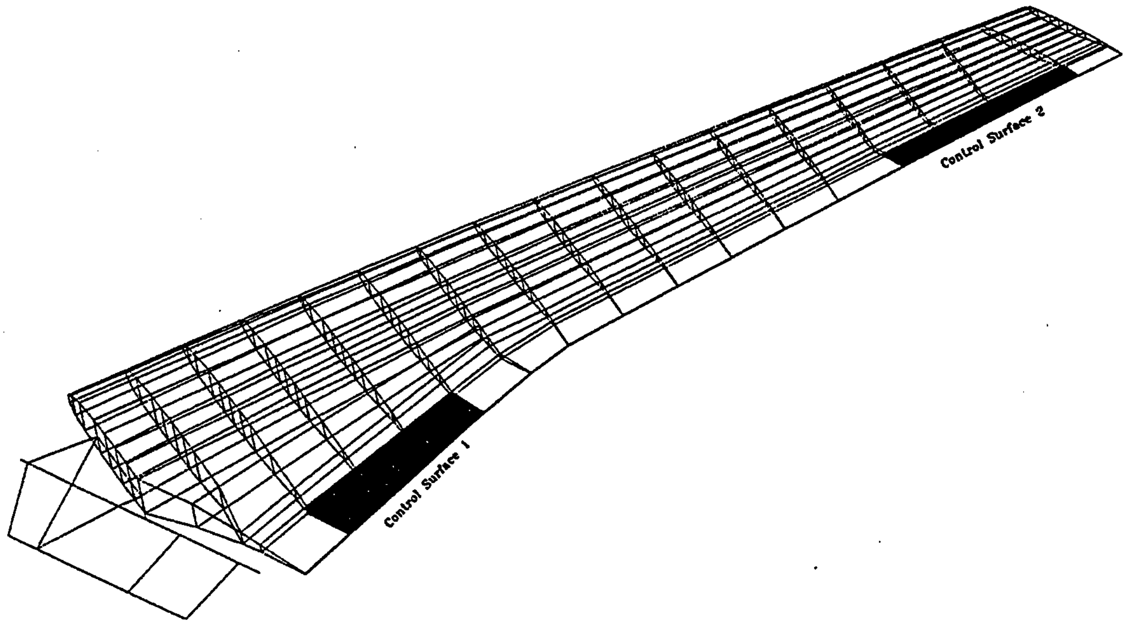


Figure 4.3.1 Structural Configuration of DAST Model by FEM.

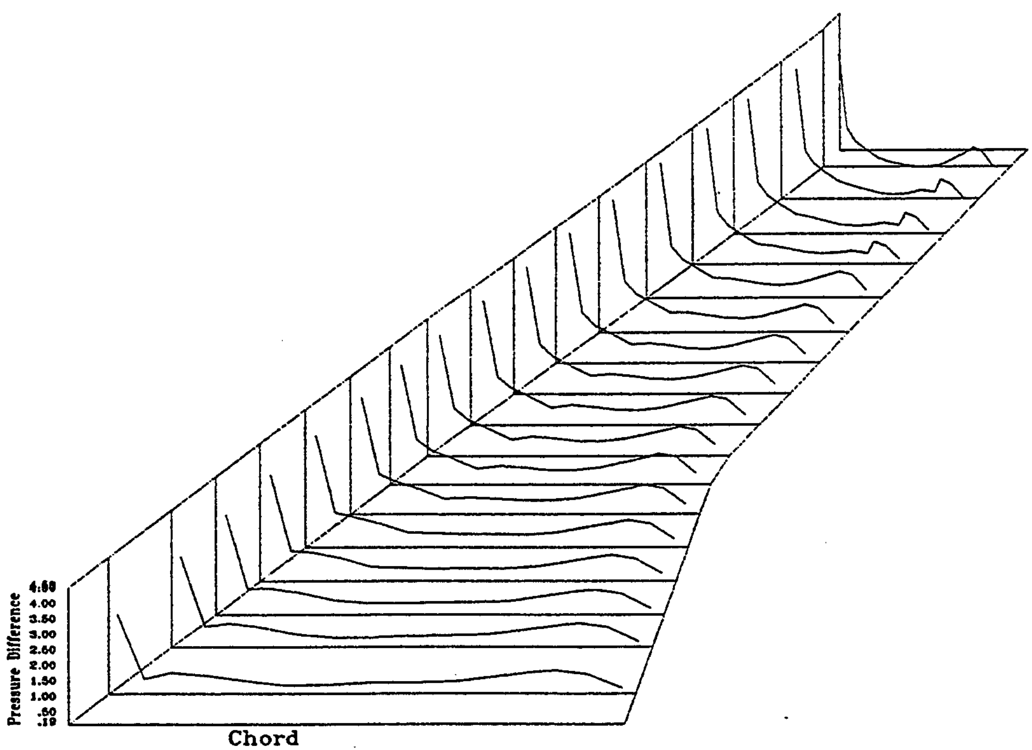


Figure 4.3.2 Pressure Distribution of DAST Model: 10*g* Pull-up Trim Condition, *M* = 0.80, by ZONA6 of ASTROS*.

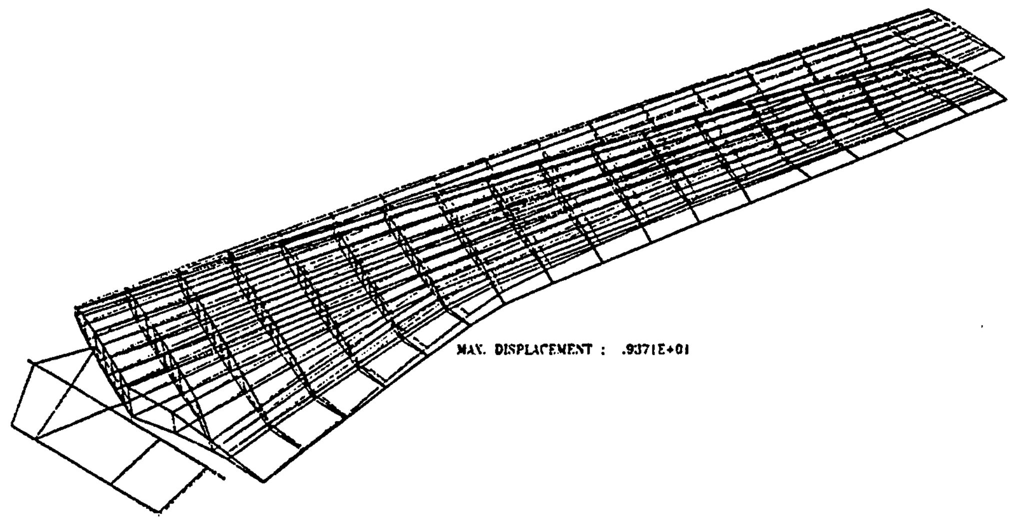


Figure 4.3.3 **Deflection Shape of DAST Model: 10*g* Trim Condition, *M* = 0.80, by ZONA6 of ASTROS*.**

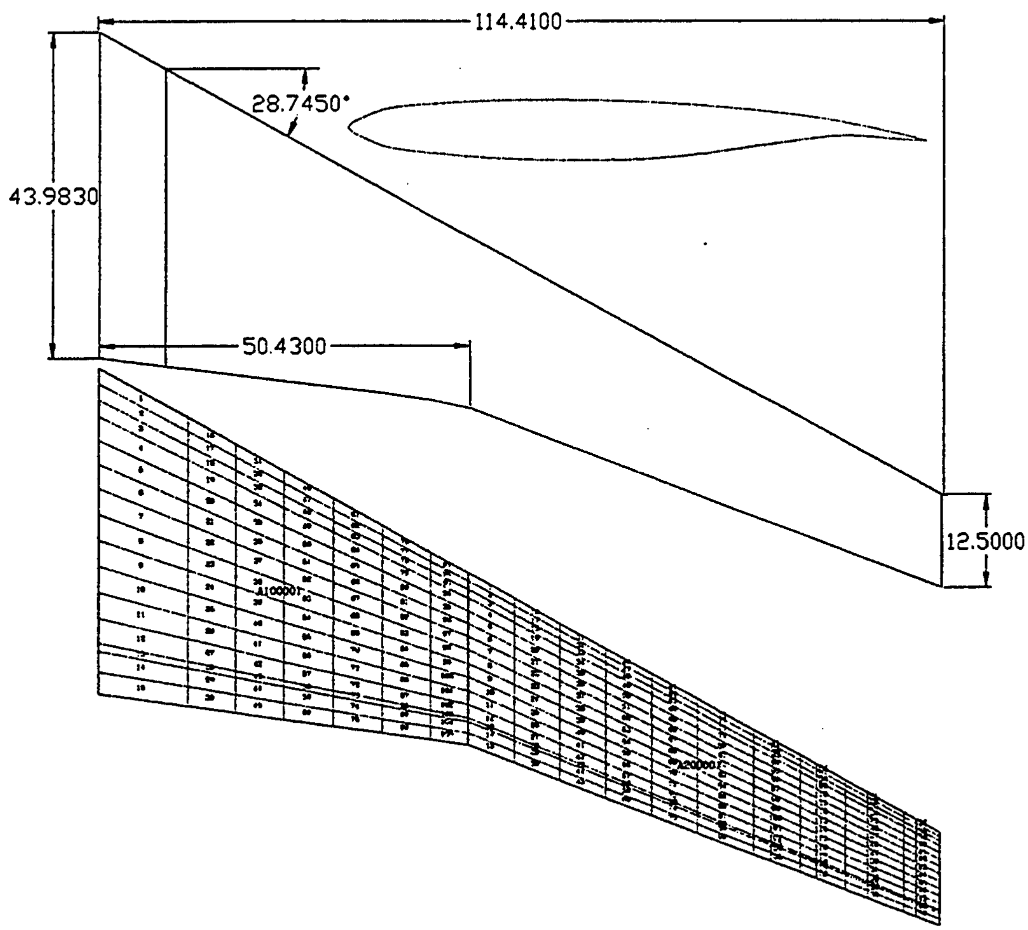


Figure 4.3.4 **Aerodynamic Planform Configuration of DAST Model.**

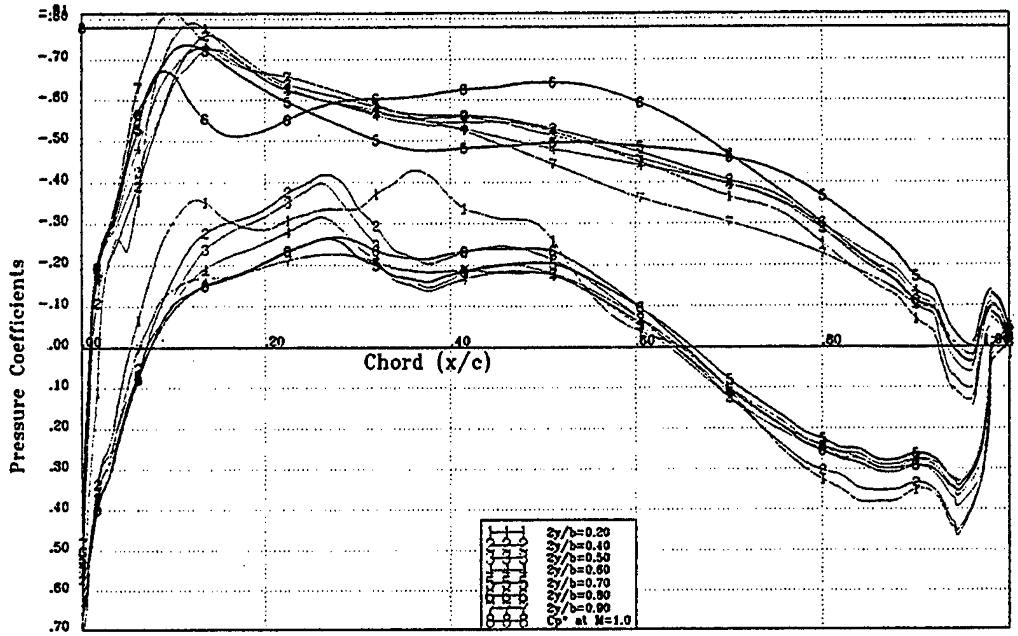


Figure 4.3.5.a **Aerodynamic Pressure Coefficients of DAST Model for Navier-Stokes Flow: $M = 0.70$, AoA $= 0.0°$, by ENSAERO.**

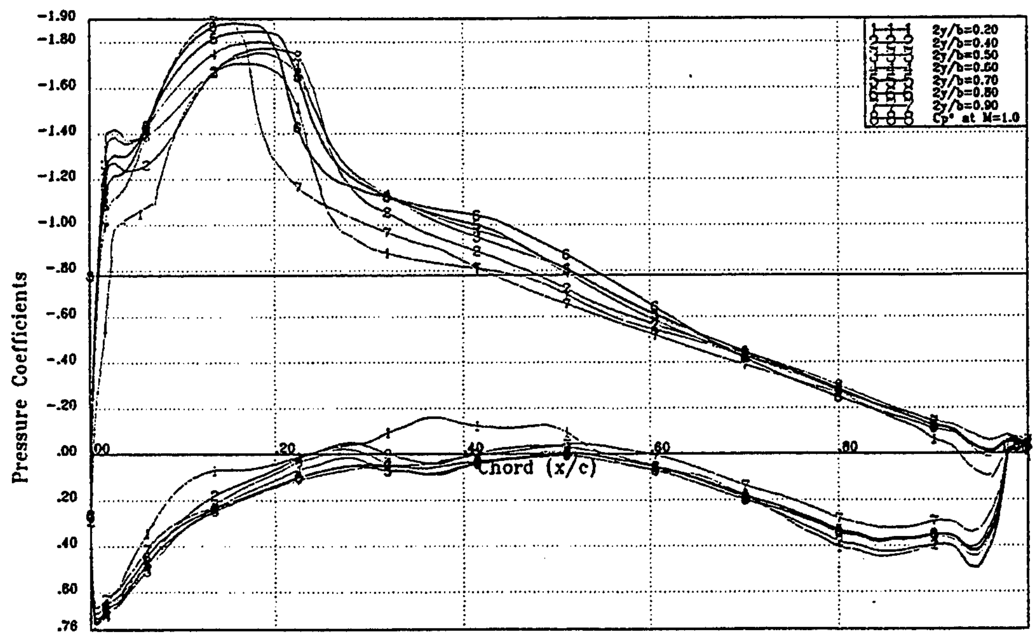


Figure 4.3.5.b **Aerodynamic Pressure Coefficients of DAST Model for Navier-Stokes Flow: $M = 0.70$, AoA=5.0°, by ENSAERO.**

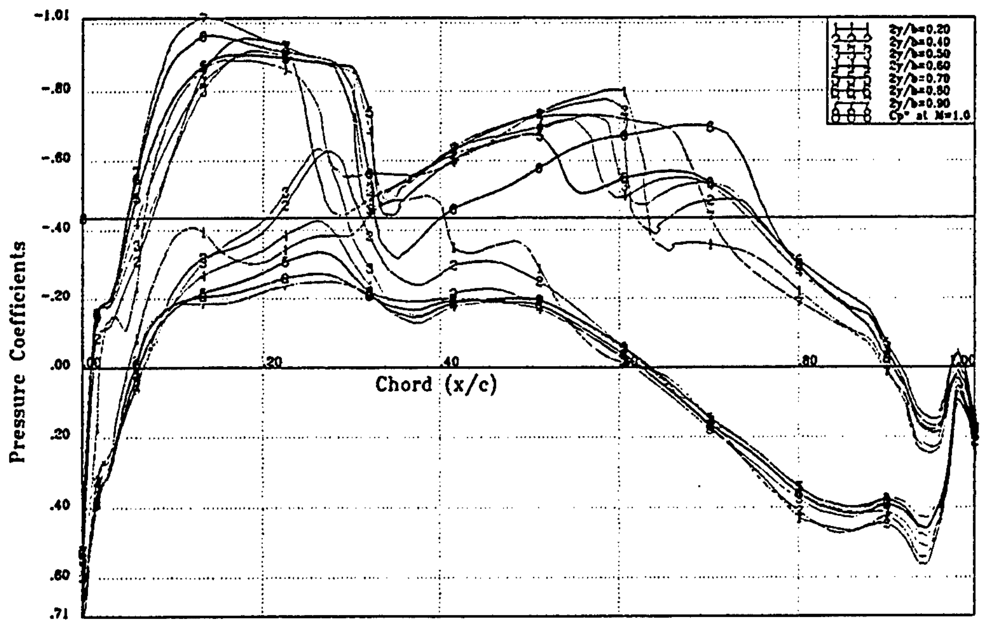


Figure 4.3.5.c **Aerodynamic Pressure Coefficients of DAST Model for Euler Flow: $M = 0.80$, AoA=0.0°, by ENSAERO.**

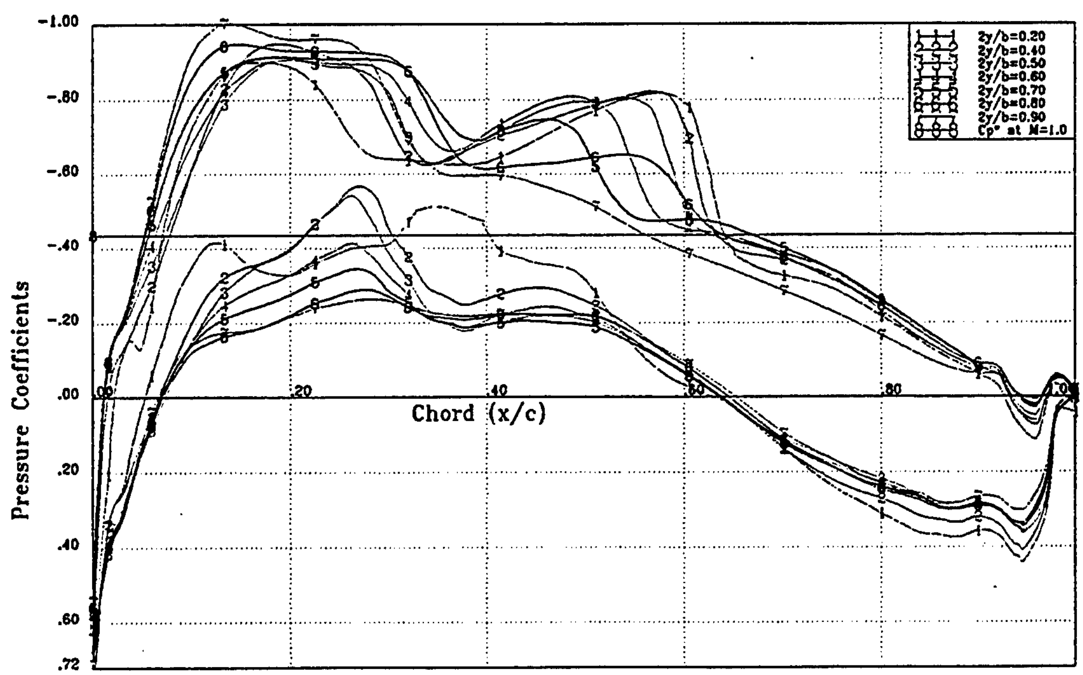


Figure 4.3.5.d **Aerodynamic Pressure Coefficients of DAST Model for Navier-Stokes Flow: $M = 0.80$, AoA=0.0°, by ENSAERO.**

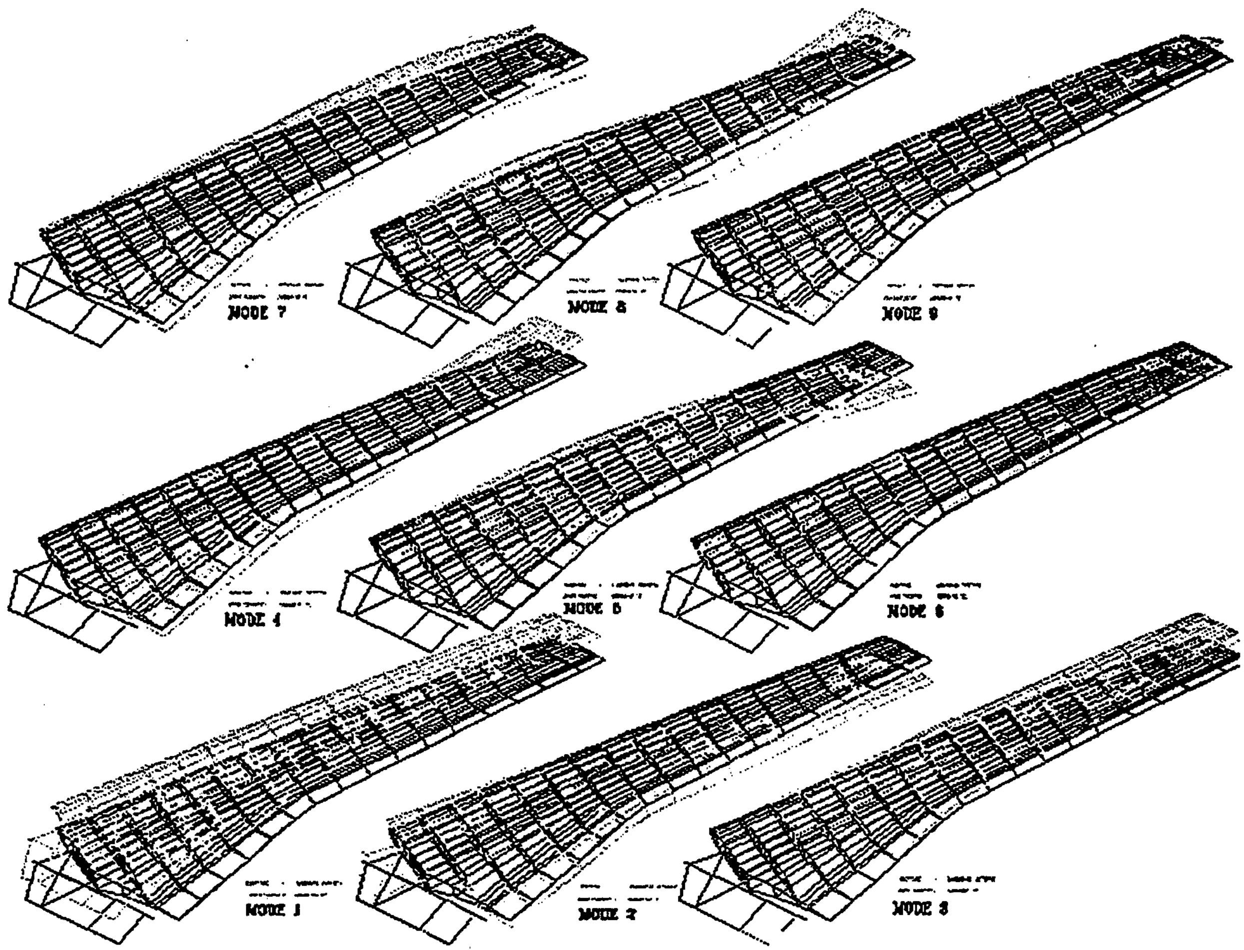


Figure 4.3.6 Normal Modes of DAST Model.

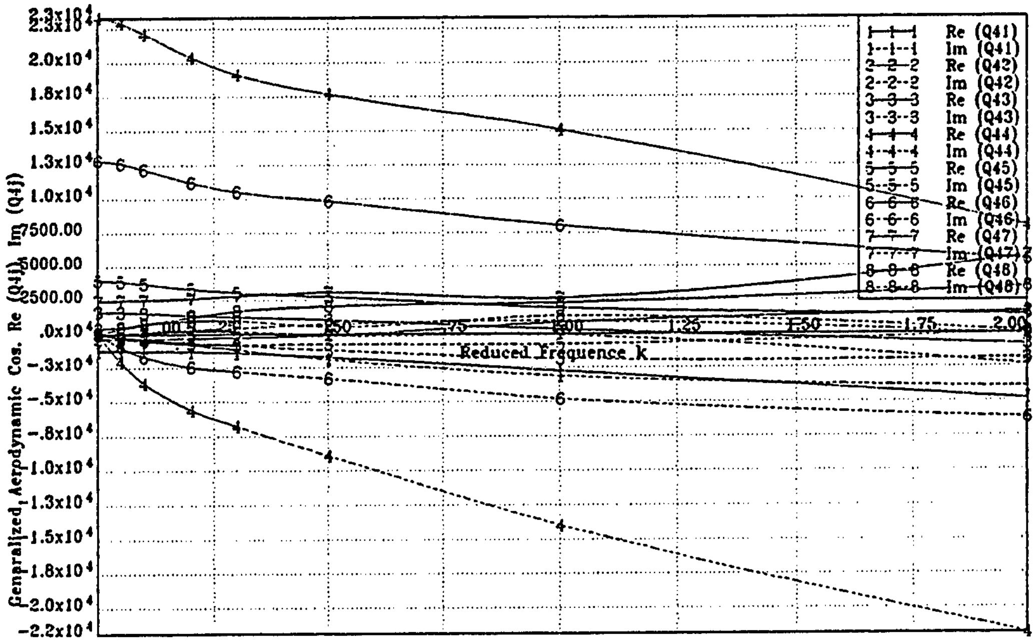


Figure 4.3.7 **Generalized Unsteady Aerodynamic Loads of DAST Model: M = 0.80, by ZONA6 of ASTROS*.**

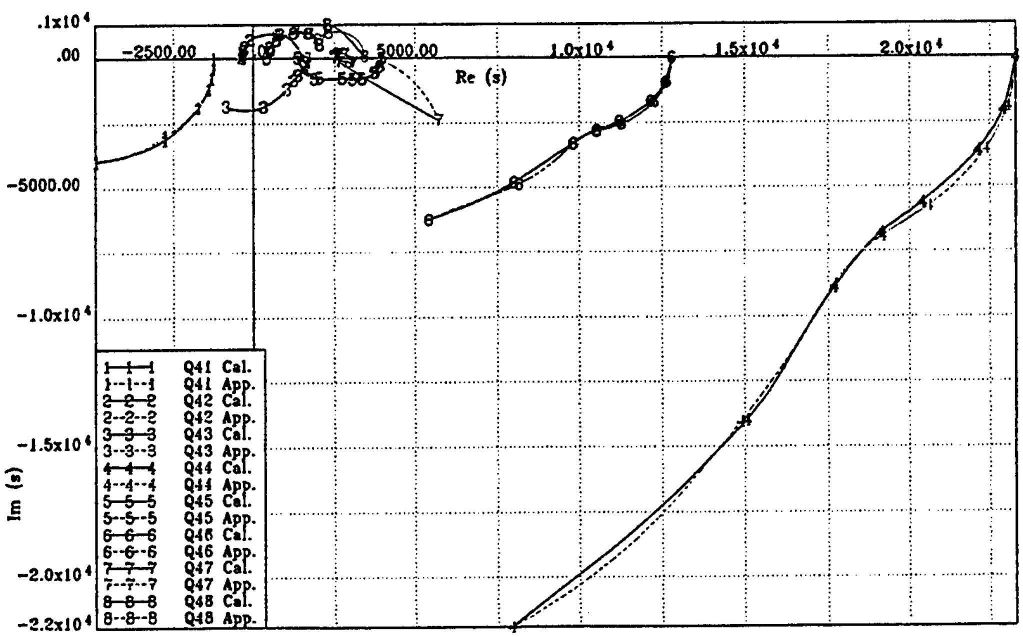


Figure 4.3.8 **Generalized Unsteady Aerodynamic Coefficients Q_{4j} of DAST Model: M = 0.80, by ZONA6 of ASTROS* and Approximated by Minimum-State Method.**

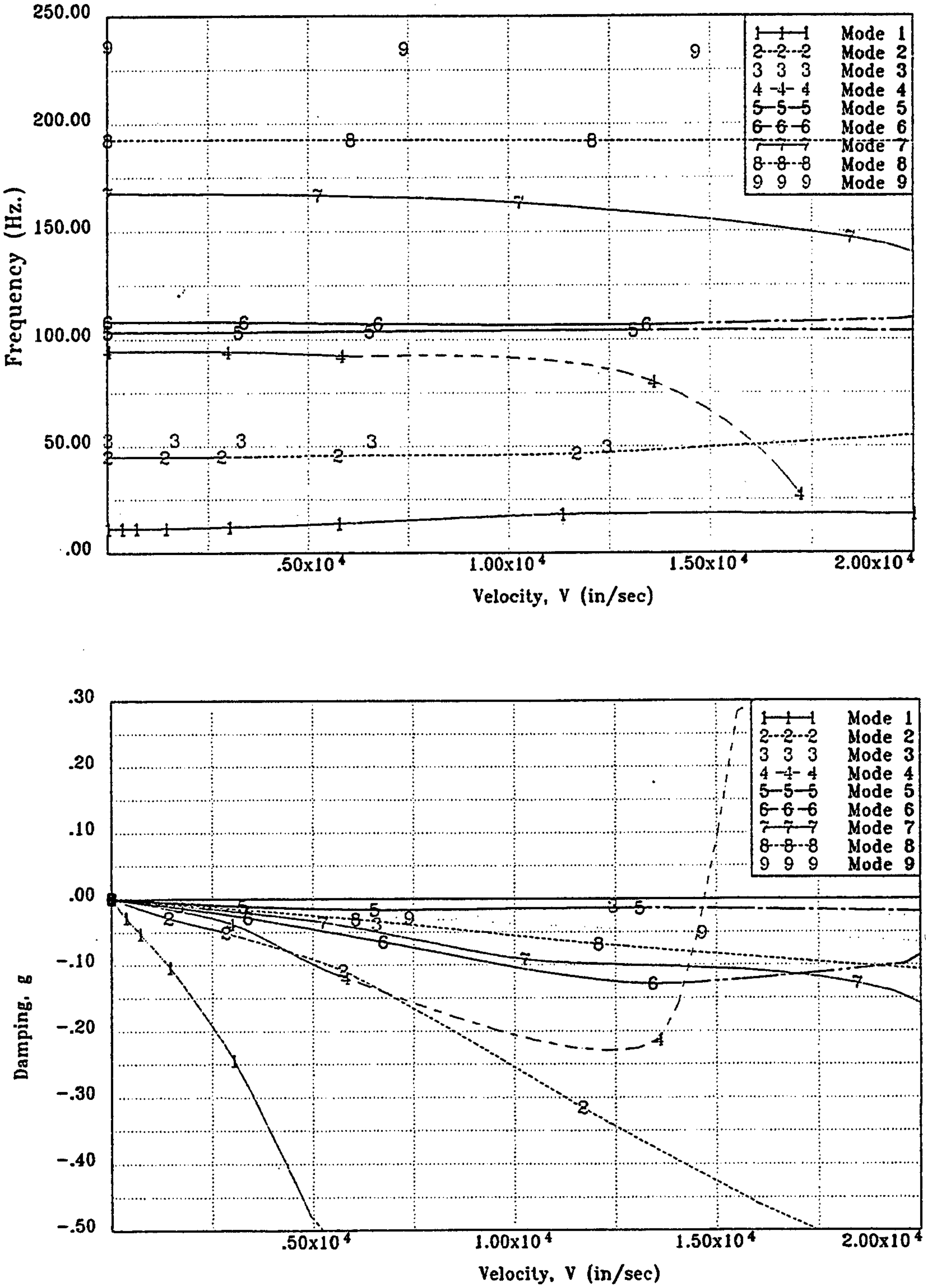


Figure 4.3.9 **V-f and V-g Plots of DAST Model: M = 0.80, by ZONA6 of ASTROS* (Flutter Speed = 14,358 *in/sec*, Flutter Frequency = 48.67 *Hz*).**

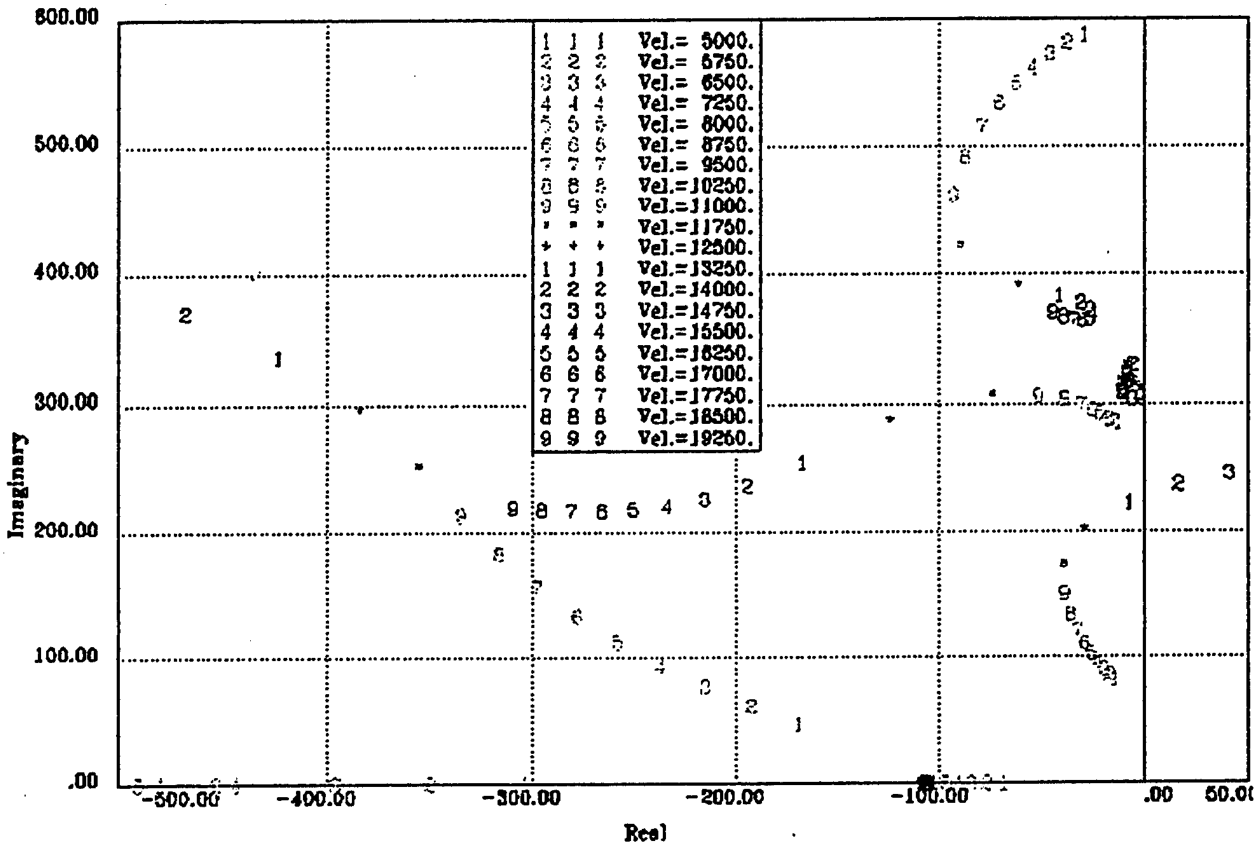


Figure 4.3.10 **Root-Locus Plot of DAST Model: *M* = 0.80, ZONA6 of ASTROS* (Flutter Speed = 13,490 *in/sec*, Flutter Frequency = 36.3 *Hz*).**

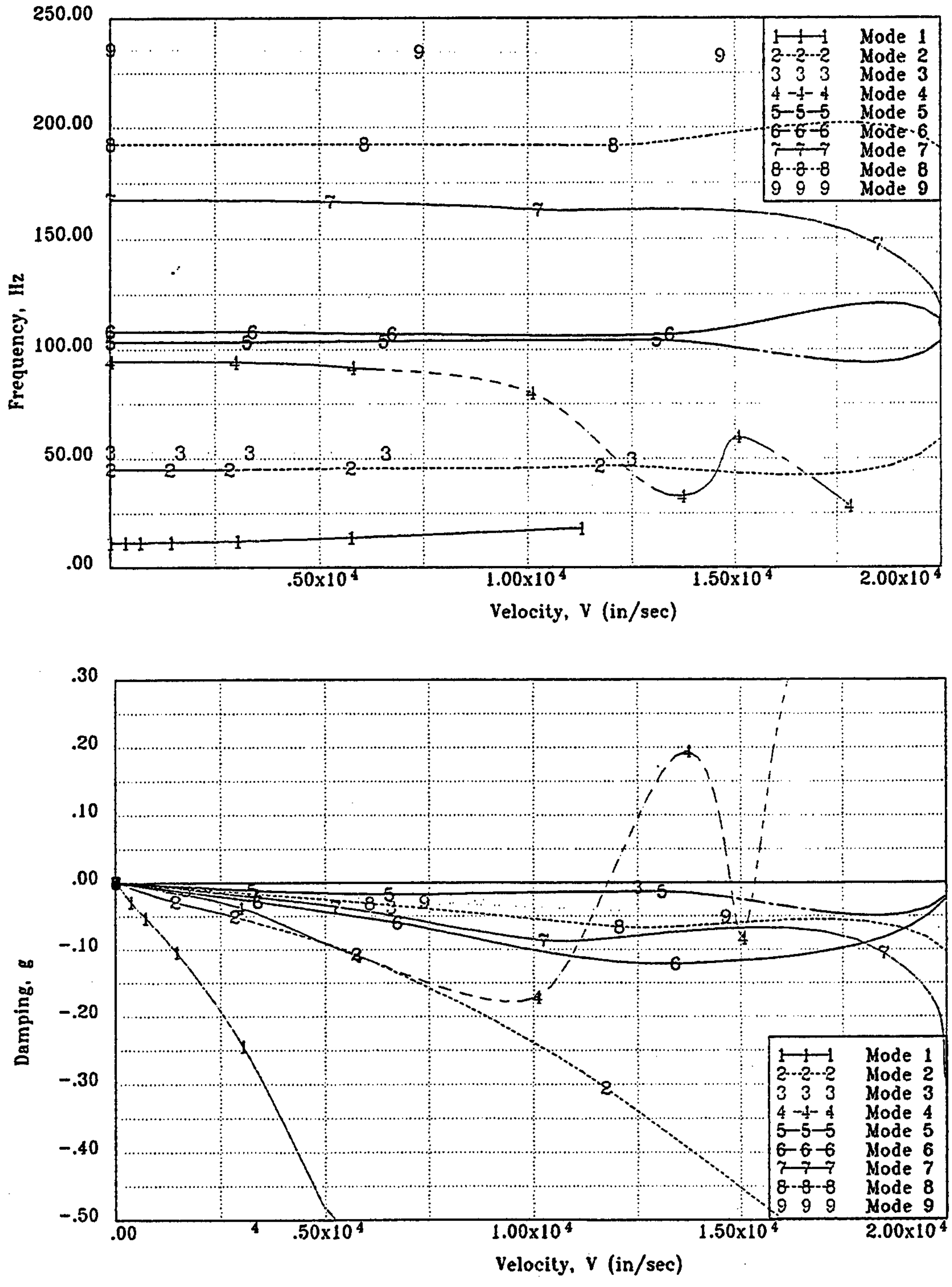


Figure 4.3.11 **V-f and V-g Plots of DAST Model: $M = 0.80$, by ZTAIC of ASTROS* (Flutter Speed = 11,800 *in/sec*, Flutter Frequency = 56.0 *Hz*)**

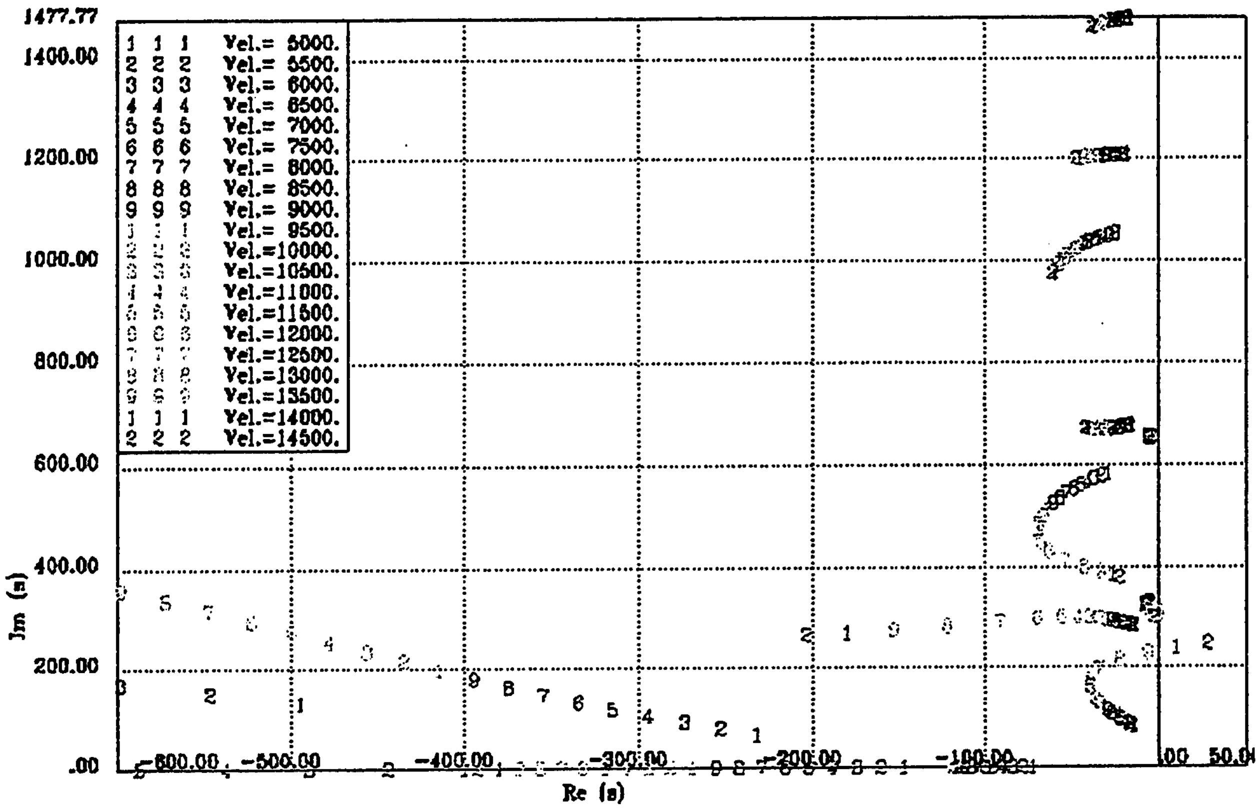


Figure 4.3.12 **Root-Locus Plot of DAST Model: *M* = 0.80, by ZTAIC of ASTROS* (Flutter Speed = 12,893 *in/sec*, Flutter Frequency = 49.3 *Hz*).**

4.4 Case 2.b: DAST (Drones for Aerodynamic and Structural Testing) Wing Model Optimization

- *Purpose:* To test a composite structural wing model in static aeroelastic, normal modes, and combined optimization.

- *Description of input and results:*

4.4.1 Static Aeroelastic Optimization

Static aeroelastic structural design optimization was performed in the 10g pull-up trim condition. The total weight of the wing skins and the spar caps was optimized. At the final design point, the trim parameters angle-of-attack and control surface deflection angle were required to match those of the analysis. The design variables were the ply thicknesses of the composite material skins and the areas of the spar caps. The minimum thicknesses of the individual plies were assumed to be 0.01 in. A displacement constraint at the wing tip, 5.506 in, was the same as the displacement from the original analysis. The Tsai-Wu failure criteria were used as strength constraints for the composite material. The required stresses in the **CBAR** elements were taken to be the von Mises stresses.

The design variables were defined by **DESVARP** entries, and each ply thickness was a design variable. Then, the properties of some of the elements were defined to the same design variables, with the effect of linking the variables. The number of properties to be determined was 989 and the number of global design variables was 254. The design variables and their numbering are shown in Fig 4.4.1.

As a result of the design optimization for static aeroelasticity, the wing weight was reduced from 89.49 *lbs* to 10.96 *lbs* in only 18 iterations. The iteration history of the design optimization is shown in Table 4.4.1. The results from the final analysis satisfied the constraints. Required CPU time was 2 hours 40 minutes 33.3 seconds.

4.4.2 Normal Modes Optimization

In the normal modes optimization, the constraint was a lower bound on the first elastic natural frequency of the structure. The required frequency was 11.288 *Hz*, the same as that calculated in the analysis of the original structure.

As a result, the weight was reduced from 89.49 *lbs* to 9.43 *lbs*. This result was obtained in only 9 iterations. The iteration history of the design optimization is shown in Table 4.4.2. The required CPU time was 18 minutes 34.0 seconds.

4.4.3 Multidisciplinary Design Optimization for Static Aeroelasticity and Normal Modes

Multidisciplinary design optimization for static aeroelasticity and normal modes was performed simultaneously. The displacements and stresses in a 10g trim condition and the lowest natural frequency were again used as the constraints.

As a result, the weight was reduced from 89.49 *lbs* to 10.86 *lbs*. This result was obtained in only 11 iterations. The CPU time was 2 hours 53 minutes 42.3 seconds. The iteration history of the design optimization is shown in Table 4.4.3 and Fig 4.4.2. The final design variables are presented in Table 4.4.4. In the layer list, 1, 2, 3, and 4 identify the 90° +45°, -45°, and 0° directions of the skin layers, respectively. Here, the thickness of the layer in the 0° direction with layer list number 4 (in the spar direction) was larger than those of the other layers.